NOV 24

MECHANICAL ENGINEERING

INCLUDING THE ENGINEERING INDEX

A Contest of Keen Minds

Plan to participate in the coming A.S.M.E. Annual Meeting whether you come to New York or not. Of course you are interested in some of the subjects treated by meeting papers published in this issue. Comment on them need not be presented in person, but may be mailed if you are not able to attend the meeting. Here is an opportunity to make your membership in the Society of inestimable value. Match your experience and wits against those of the authors and enjoy the stimulus that follows a contest of keen minds and the satisfaction of contributing to engineering progress.

MID-NOVEMBER 1926

THE MONTHLY JOURNAL PUBLISHED BY THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

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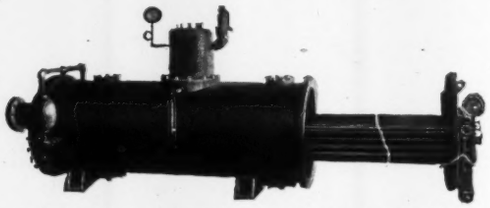

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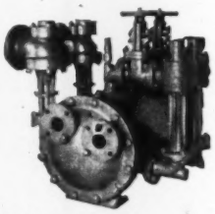

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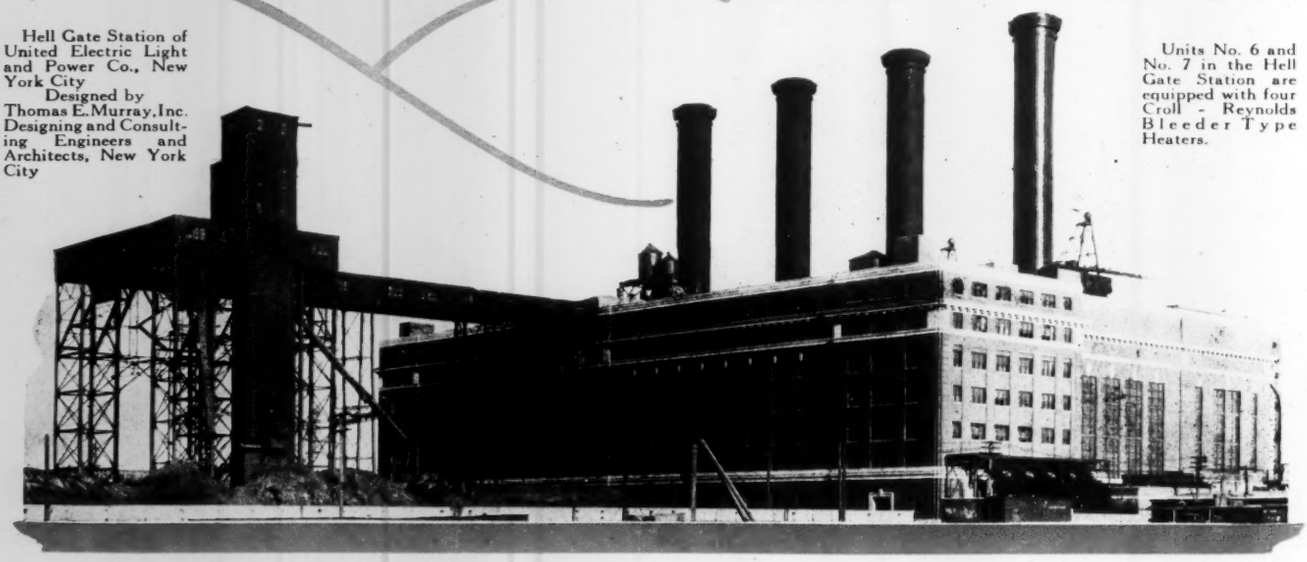

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Mechanical Engineering

The Monthly Journal Published by

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Volume 48 November, Part 2, 1926 Number 11a

CONTENTS OF THIS ISSUE

The Use of High Steam Pressure in Locomotives	*E. C. Schmidt and J. M. Snodgrass*	1195
Theory of Milling Cutters	*N. N. Sawin*	1203
The Distillation of Coal	*W. H. Blauvelt*	1210
Complete Gasification of Bituminous Coal	*R. S. McBride*	1213
The Low-Temperature Carbonization of Coal	*A. C. Fieldner*	1217
A Mercury Compressor Evolved from the Archimedes Screw Pump	*J. G. DeRemer*	1228
Development and Construction of the Standard Army Parachute	*John Bonforte*	1234
The Fusion-Joining of Metallic Materials in Aircraft Construction	*S. Daniels*	1240
Railroad Organization	*J. C. Clark*	1247
Vitalizing vs. Centralizing Organizations	*R. E. Newcomb*	1251
Industry's Annual Tax for Materials Handling and Suggestions for Its Elimination	*H. V. Coes*	1253
Trades Training	*C. S. Coler*	1257
Educational Training for Industry	*Matthew Woll*	1261
The Tangent Method of Analysis for Indicator Cards of Internal-Combustion Engines	*P. H. Schweitzer*	1263
Smoke Abatement, Its Effects and Its Limitations	*H. B. Meller*	1275
Present Status of the Smoke Problem	*Osborn Monnett*	1284
Wood Finishing—A Glance Ahead	*F. L. Browne*	1286
The Use of Wood Lacquer Finishes	*W. S. Edgar*	1289
A Study of Various and Lacquer Finishes Exposed to Accelerated Breakdown Tests	*P. S. Kennedy*	1291
Technology of Wood Stains and Fillers for Use with Lacquer	*S. M. Silverstein*	1293
Determination of Thermal Conductivities of Insulation for Temperatures up to 1000 Deg. Fahr. on Other than Flat Surfaces	*R. H. Heilman*	1297
Status of Heat-Transmission Data and Knowledge in the Refractory Field	*P. Nicholls*	1307
Some Results of Condenser Operation	*E. B. Ricketts*	1312
The Modern Oil Engine	*E. C. Magdeburger*	1315
A Temperature-Entropy Diagram for Air and the Diatomic Gases O_2, N_2, and CO	*H. A. Everett*	1329
Guarded-Plate-Heater Method of Testing Low-Temperature Insulators Compared with Several Box Methods	*E. F. Grundhofer*	1333
Methods That Have Been and Are Being Used for Measuring Heat Transmission	*F. G. Hechler*	1337
New Methods of Lubricating Steel-Mill Machinery	*C. H. Bromley*	1344
Power-Station Accounting for Industrial Plants	*W. R. Herod*	1347
Joint Research Committee on Boiler-Feedwater Studies—Reports of Sub-Committees		1361
Synopses of Other Annual Meeting Papers		1375
Contributors to this Issue		1379

ADVERTISING

Power Show Guide	1	Alphabetical List of Exhibitors	68
Introductory	3	Classified List of Advertisers' Products	124
Floor Diagrams	36	Alphabetical List of Advertisers	136

Price 60 Cents a Copy, $5.00 a year: to Members and Affiliates, 50 Cents a Copy, $4.00 a year. Postage to Canada, 75 Cents Additional; to Foreign Countries $1.50 Additional. Changes of address should be sent to the Society Headquarters.

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Wednesday Afternoon, December 8

2:00 P.M.

Business Meeting and General Session.

3:00 P.M.

Education and Training for the Industries.

Educational Training for Industry, MATTHEW WOLL.

Trades Training, CARL S. COLER.

3:00 P.M.

Student Branch Conference.

Steam Tables Research.

Several reports will be presented.

3:30 P.M.

Ladies' Tea at Hotel Astor.

Wednesday Evening, December 8

Annual Dinner at Hotel Astor

Introduction of New Members. Address by President-elect Charles M. Schwab.

Thursday Morning, December 9, 9:30 A.M.

Central Station Power

Operating Performance of Modern Surface Condensers, PAUL A. BANCEL.

Some Results of Condenser Operation, EDWIN B. RICKETTS.

Steam-Condenser Practice and Performance, F. J. CHATEL.

The Influence of Radiation in Coal-Fired Furnaces on Boiler Requirements and a Simplified Method for Its Calculation, W. J. WOHLENBERG and E. L. LINDSETH.

Accuracy of the V-Notch Weir Method of Measurement, D. ROBT. YARNALL.

Management (I)

The Laws of Manufacturing Management, L. P. ALFORD.

Production Control, C. G. STOELL.

Machine Shop Practice (II)

Chromium Plating, WILLIAM BLUM.

The Change of Viewpoint of the Machine Shop, A. L. DELEEUW.

Theory of Milling Cutters, N. W. SAWIN.

Aeronautic

Fusion Joining of Metallic Materials in Aircraft Construction, SAMUEL DANIELS.

Development and Construction of the Standard Army Parachute, JOHN BONFORTE.

The Flettner Rotor and Its Industrial Applications, F. O. WILLHOFFT.

Thursday Afternoon, December 9, 2:00 P.M.

Management (II)—Jointly with Taylor Soc.

Problems of Organization:

Railroad Organization, J. C. CLARK.

Vitalizing vs. Centralizing Organizations, R. E. NEWCOMB.

Problems of Bank Organization, H. A. HOPF.

An Experiment in Scientific Management in the Coal-Mine Industry, JEROME C. WHITE.

Oil and Gas Power

Kinematics of Cams Calculated by Graphical Methods, H. SCHRECK.

Two-Cycle Oil Engines, E. C. MAGDEBURGER.

Ideal Gas-Engine Cycles, R. C. H. HECK.

A Temperature-Entropy Diagram for Air and the Diatomic Gases O_2, N_2, and CO, H. A. EVERETT.

The Tangent Method of Analysis for Indicator Cards of Internal-Combustion Engines, P. H. SCHWEITZER.

Machine Shop Practice (III)

Worm-Wheel Contact, EARLE BUCKINGHAM.

The Plastic Behavior of Metal in Drawing, C. L. EKSERGIAN.

A Study of the Distribution of Belt Creep and Slip, R. F. JONES.

Henry Robinson Towne Lecture, 4:30 P. M.

The Credit Factor in the Structure of Industry, PROF. DAVIS R. DEWEY, Department of Economics, Massachusetts Institute of Technology, Cambridge, Mass.

Petroleum

New Method of Lubrication of Steel-Mill Machinery, CHAS. H. BROMLEY.

The Boiler House in Oil Refineries, H. A. ROSS.

Modern Fire Fighting in Oil Refineries, F. A. EPPES.

Power—Jointly with Research Committee on Boiler Feedwater

Progress Reports of 9 Sub-Committees.

Thursday Evening, December 9

College Reunions

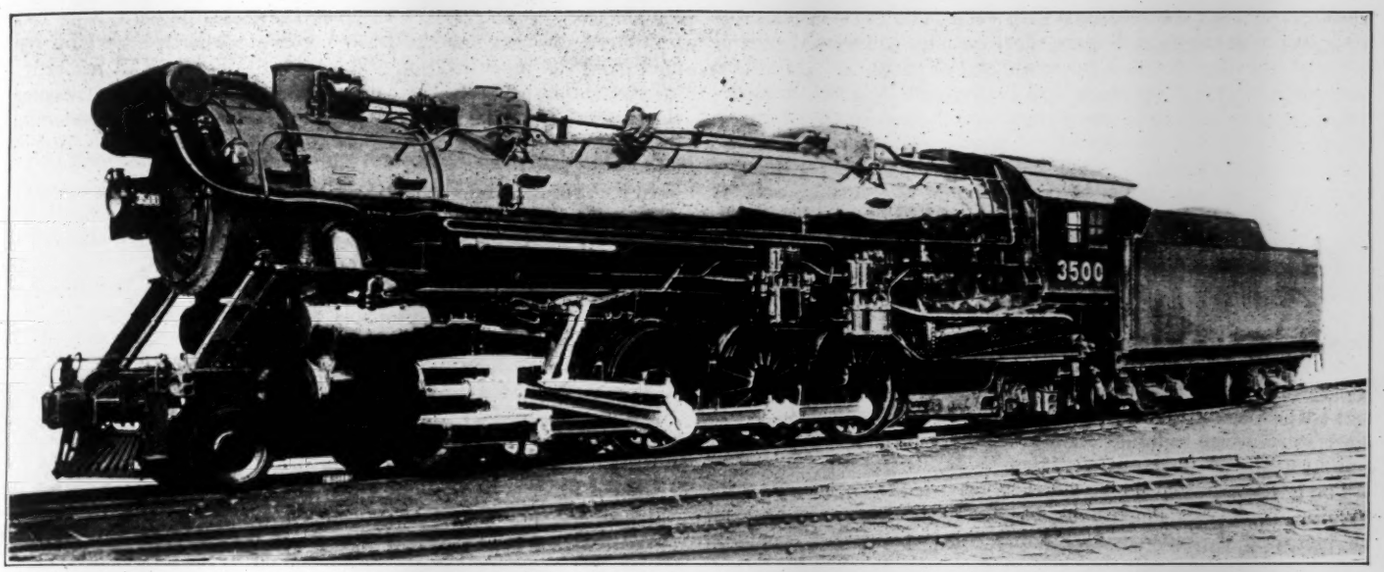

FIG. 1 NEW YORK, NEW HAVEN & HARTFORD RAILROAD LOCOMOTIVE NO. 3500, EQUIPPED WITH MCCLELLON BOILER

The Use of High Steam Pressure in Locomotives

A Summary of the Advantages of Using High Steam Pressures in Reciprocating Locomotives, and a Review of the More Notable Applications of Steam Pressures of 240 Lb. Per Sq. In. or Higher

BY EDWARD C. SCHMIDT[1] AND JOHN M. SNODGRASS,[2] URBANA, ILL.

THIS paper, prepared at the request of the Executive Committee of the Railroad Division, is intended to be a summary of the advantages of using high steam pressures in reciprocating locomotives, and a review of the more notable applications of steam pressures of 240 lb. per sq. in. or higher.

In the older current locomotives the working pressure lies generally between 180 and 210 lb. gage; in those of recent construction it varies from 200 to 250 lb. The last-mentioned pressure is still unusual, and of the 70,000 locomotives on the railroads of the United States, fewer than a thousand carry this pressure, which is the present maximum in locomotive boilers of standard design. The practice abroad has not differed much from our own in this respect.

In the use of high pressures locomotive practice has lagged behind that in stationary plants, chiefly because of the difficulty of adapting the water-tube boiler to locomotive conditions. Within the last ten years the working pressure in central generating stations has been increased to about 600 lb. per sq. in.; and for special purposes, in small boilers of special design, the working pressure has been carried as high as 1500 lb.

The firebox of the ordinary locomotive has extensive flat surfaces whose proper staying becomes more difficult as the working pressure is increased. While the maximum pressure for which it is possible properly to stay the ordinary firebox is not yet definitely settled, it probably lies between 275 and 300 lb. In view of this fact and of the pressures in current use the term "high steam pressure" may be defined for the purposes of this presentation as a pressure of 300 lb. or more. Since, however, there are at present only two reciprocating locomotives using so high a pressure, certain facts are presented about those locomotives which operate at or near the usual current maximum pressure, namely, 250 lb.

Increasing the train load has always been, in American practice, the usual resort for attaining economy in general operation, and it has resulted in an unremitting demand for locomotives of greater capacity or tractive effort. For the locomotive designer an increase in steam pressure is an easy way to a moderate increase in capacity, and there has been a steady increase in boiler pressure from the earliest days of locomotive construction; the progress, however, has thus far been made by small steps of 10, 15, or 20 lb. at one time, and it has generally involved no radical departures in design. Interest in higher pressure is no new thing; what distinguishes our present interest in the subject is that the contemplated pressure increases far exceed our previous changes—the pressure used in two American locomotives is 100 and 150 lb. in excess of the current maximum, and in the high-pressure locomotive of the German State Railways, later to be described, the excess is 600 lb.

Twenty-five years ago there was considerable discussion of this subject, although it was then conceived in terms rather different from those in which we view it today. Under the demand for increased capacity the locomotive designer was confronted with the question as to whether to get this increase by using higher pressure or by applying a larger boiler and using steam of the then current pressures in larger cylinders. The common pressures of the time were 180 to 200 lb.; 250 lb. was then considerably in advance of any existing practice. Dr. W. F. M. Goss, in 1904 and 1905, undertook experiments[3] to try to settle this question. He measured the performance of a locomotive using saturated steam in single-expansion cylinders, operated under boiler pressures of 120 160, 180, 200, and 240 lb. per sq. in. These tests defined the direct gains due to higher pressure, and also the evaporation per pound of coal under different rates of combustion and of evaporation. He then calculated the increased heating surface which might be obtained if the increase in boiler weight required by the higher pressures were used instead to produce a boiler of ampler heating surface which would operate under the lower pressure and—by virtue of its greater heating surface—under a more economical rate of combustion. The results indicated that for pressures of 180 lb. and above the gain due to increased pressure would be nearly or quite offset by the gain in evaporative efficiency obtainable from the larger boiler of like weight. After making due allowance for the increased difficulty and cost of maintenance at the higher pressures, Dr. Goss

[1] Professor of Railway Engineering, University of Illinois. Mem. A.S.M.E.
[2] Professor of Railway Mechanical Engineering, University of Illinois. Mem. A.S.M.E.

Contributed by the Railroad Division for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. All papers are subject to revision.

[3] High Steam Pressures in Locomotive Service. Publication No. 66 of the Carnegie Institution of Washington. Summarized in Bulletin 26 of the Engineering Experiment Station of the University of Illinois.

Be sure to bring this copy with you to the Annual Meeting

concluded that for the pressures under consideration and for saturated steam in simple cylinders there was no substantial overall economy in using pressures in excess of 180 or 200 lb. His chief conclusions were: "Assuming 180 lb. pressure to have been accepted as standard, and assuming the maintenance to be of the highest order, it will be found good practice to utilize any allowable increase in weight by providing a larger boiler rather than by providing a stronger boiler to permit higher pressures."—and "A simple locomotive using saturated steam will render good and efficient service when the running pressure is as low as 160 lb.; under most favorable conditions, no argument is to be found in the economic performance of the engine which can justify the use of pressures greater than 200 lb." In comparing these conclusions with the views held today it must be borne in mind that the design of recent locomotives has encroached much further upon the available space and weight limits than did the locomotive of two decades ago, that we are now using superheated steam, and that never before in the history of the railroads has the necessity for the greatest economy in steam and coal been so urgent.

The interest in high boiler pressure persisted, however, notwithstanding Dr. Goss's conclusions, because at the time, the demand for increased capacity overshadowed considerations of economy. The situation in America was presently greatly relieved by the introduction of superheated steam which, although it had been for some years in use on European roads, was first extensively applied here to locomotives on the Canadian Pacific Railway about 1905. The great gain in capacity and economy resulting from its use far exceeded anything to be hoped for from such increases in steam pressure as were then under consideration, and proposals for general pressure increases were temporarily dropped.

THE ADVANTAGES TO BE DERIVED FROM HIGH PRESSURE

The reasons for considering higher pressure in locomotive service and the advantages to be derived from its use may be stated as follows: (1) The use of higher steam pressure results in a considerable decrease in steam consumption, and a corresponding—though slightly smaller—decrease in coal consumption. (2) Within the usual fixed limits of width and height the locomotive designer may obtain greater tractive force and greater power by increasing the boiler pressure. It is fortunately possible to obtain simultaneously both these benefits; and it is not necessary, as in some locomotive-economy-promoting devices, to trade economy for capacity or vice versa.

If the new high-pressure type of boiler proves ultimately to be inherently lighter than the present standard boiler, then, for a given total engine weight, it will be possible to obtain greater tractive force with high steam pressure; but we cannot know whether this will be true until the new type of boiler has been further developed and perfected.

The magnitude of the gains to be derived from high pressure is illustrated by the Rankine-cycle efficiencies shown in Table 1,

TABLE 1 SHOWING RANKINE-CYCLE EFFICIENCIES FOR SINGLE-EXPANSION CYLINDERS, USING STEAM AT VARIOUS INITIAL PRESSURES, SUPERHEAT OF 250 DEG., AND EXHAUSTING AGAINST 20 LB. ABSOLUTE BACK PRESSURE

Initial steam pressure, lb. per sq. in. gage	Temperatures — Of the saturated steam, deg. fahr.	Temperatures — Of the superheated steam, deg. fahr.	Rankine-cycle efficiency, per cent	Gain in efficiency over that attained with 200 lb. initial pressure, per cent	Increment of gain, per cent
200	388.0	638.0	18.90	.....	....
250	406.2	656.2	20.34	7.61	7.61
300	421.9	671.9	21.50	13.75	6.14
350	435.9	685.9	22.49	19.00	5.25
400	448.4	698.4	23.38	23.70	4.70
500	470.2	720.2	24.81	31.28	7.58
600	489.1	739.1	25.98	37.46	6.18
700	505.7	755.7	26.95	42.59	5.13
800	520.6	770.6	27.76	46.88	4.29
900	534.2	784.2	28.47	50.63	3.75

for pressures varying from 200 to 900 lb., at 250 deg. superheat, and an absolute back pressure of 20 lb. per sq. in. The fifth column shows the gains in efficiency expressed as percentages of that attained at 200 lb. pressure; it will be noted that 400-lb. steam gives 23.70 per cent greater efficiency than 200-lb. steam, and 800-lb. steam gives 46.88 per cent more than 200-lb. In view of the difficulties of utilizing extremely high pressures on locomotives, it is significant to observe that the increment of gain decreases as the pressure is increased. As indicated in the last column of Table 1, the efficiency to be gained by raising the steam pressure from 200 to 300 lb., for example, is 13.75 per cent; whereas the gain by increasing the pressure from 800 to 900 lb. is only 3.75 per cent; in other words, while the total gain in efficiency secured by increasing the pressure from 200 lb. to 900 lb. is over 50 per cent, the first 100-lb. stage of the increase gives more than $3\frac{1}{2}$ times as much benefit as does the last 100-lb. stage.

In reciprocating non-condensing engines operating with moderate pressure and under excellent conditions, the actual efficiency has proved to be from six-tenths to seven-tenths of the ideal efficiency shown in Table 1. The proportion varies, depending on whether the engine is operated simple or compound, and upon the amount of superheat. There will probably be no very radical modification of this proportion with the use of higher pressure, and we are warranted in expecting that the relation between the actual efficiencies at various pressures will not differ greatly from the relation between the theoretical efficiencies shown in the table. Such considerations make it certain that the gains attainable by the use of high pressures are very considerable and well worth striving for.

As has already been pointed out, the second advantage, namely, the increase in tractive force attainable with high pressures, has always been of great importance and it has become more and more so as locomotive design has approached closer to the weight limits and to the space limits set by the track clearance, which have been nearly or quite reached in many instances. Anything which under these conditions will permit the designer to continue to produce a more powerful machine which will draw a heavier train is bound to be regarded as of the utmost importance by every railroad operating officer, for it opens again the avenue to highest operating efficiency and economy.

Both advantages are important, and which one is regarded as the more so will depend upon the circumstances. Probably in European practice, with their light train load and high fuel cost, the gain in economy will seem more important than the gain in power; although present fuel costs on American roads have mounted to a point where our attitude toward such an engineering problem must be quite different from what it might properly have been ten years ago.

These two advantages of high steam pressure have been variously stated and explained and it may be of interest to quote some of these statements. In an article on Future Possibilities of Locomotive Design,[4] Louis H. Rehfuss says, for example:

> The whole reason for this trend toward high pressures lies in the fact that while the total heat to be imparted to a pound of water remains practically the same at all pressures, the heat of vaporization, which is never available as mechanical energy, steadily decreases as the pressure increases. This means that as the pressure rises, a steadily increasing percentage of the heat is available as useful work. Theoretical savings, of course, are larger than the practical, because of the greater condensation occurring at the higher temperatures, and of other factors. . . . . The necessity for high steam capacity is obviated by the use of high pressures. Thus a pound of saturated steam at 500 lb. pressure occupies but 0.90 cu. ft. contrasted with the 2.14 cu. ft. occupied by saturated steam at our customary 200-lb. pressure. When the increased power available in the higher-pressure steam is also taken into consideration, it will be seen that the steam capacity with 500 lb. pressure need be but a third of that used with the 200 lb. pressure employed today.

Speaking at the exercises held on the Delaware & Hudson Railroad when the *Horatio Allen* was placed in service, John E. Muhlfeld, the designer of this engine, said:[5]

> It was designed to determine what might be accomplished in the better production and utilization of fuel heat, by means of high steam pressure and the greater use of its expansive properties, in combination with the development of maximum hauling power in the most simplified form of a modern steam locomotive, consisting of two cylinders and four pairs of driving wheels. To illustrate, assume that to convert a certain amount of water into steam at 200 lb. pressure, 1199.2 lb. of coal must be used. To increase the 200 lb. pressure to 350 lb. only 7.4 lb. more coal must be used, and this increase of less than 0.62 per cent in fuel gives an increase of 150 lb., or 75 per cent, in power. Then instead of using the steam of 350 lb. pressure, direct from the boiler in both the right and left cylinders and exhausting it out of the stack, it is used first in the right and again in the left cylinder, and by this double-expansion process the heat that has been put into the steam is more effectively utilized before it is exhausted to the atmosphere. By this combination it is calculated that the saving in fuel consumption per unit of work done by the locomotive when working in compound gear, as compared with the ordinary single-expansion cylinder

[4] *Railway Mechanical Engineer*, vol. 100, no. 4, April, 1926.
[5] *Railway Review*, vol. 75, no. 4, Dec. 13, 1924, p. 939.

locomotive, will be: First, the gain from increasing the steam pressure from 200 to 350 lb. will represent about 15 per cent less fuel consumed per drawbar horsepower-hour. Second, the gain through double expansion of the steam will represent about 17 per cent less fuel consumed per drawbar horsepower-hour. Third, etc.....

On the other side of the account there are some difficulties in the design and operation of high-pressure locomotives which, while probably not insuperable, ought nevertheless to receive due consideration. As has been intimated, the use of pressures above 300 lb. has entailed and will entail radical departures in boiler design. The experience with the Brotan boiler, having a firebox of water-tube construction, has, however, been extensive and encouraging. Similar types of construction have been used in the *Horatio Allen* and in the high-pressure locomotive built by Henschel & Sohn for the German State Railways. While the maintenance of such boilers, the maintenance of valves and piping, and lubrication under high temperature will introduce problems new to the railroad man there is in the results attained in high-pressure stationary plants ground for the hope that these problems can be satisfactorily solved; and the experience of the New York, New Haven & Hartford Railroad with the McClellon boiler offers similar encouragement.

In the opinion of many railroad men, one of the most serious problems to be solved in adapting the high-pressure water-tube type boiler to American railroad conditions lies in the almost universal use of untreated boiler waters on our railroads. Under the high temperature of the high-pressure steam the scaling is sure to be serious, and the proper washing and cleaning of these boilers will interpose a serious objection to their widespread use. Such an objection is not, of course, insurmountable, but it will undoubtedly greatly retard the adoption of high-pressure locomotives in many situations.

The maximum steam temperature which it is possible to carry without impairing the strength of the engine parts or without incurring unusual difficulties in lubrication remains to be determined. The maximum safe temperature is commonly held to be not over 750 deg. fahr., although the basis for this opinion is not generally stated. Fortunately the maximum steam temperature contemplated for locomotives does not greatly exceed this present limit. At 900 lb. pressure and 250 deg. superheat, for example, the temperature of the steam is 784 deg., which is only 146 deg. more than the temperature of 200-lb. steam with the same superheat (638 deg.). In high-pressure stationary plants the steam temperature runs in the neighborhood of 700 deg. to 725 deg. It seems likely that the difficulties arising from such increases in temperature as are entailed by the use of steam of even 900 lb. pressure can ultimately be overcome.

HIGH-PRESSURE LOCOMOTIVES IN SERVICE OR UNDER CONSTRUCTION

As previously stated, in view of the very small number of locomotives actually in service using high pressure as above defined, it has seemed useful to list here not only those using pressures in excess of 300 lb., but also some of those operating at or near the current maximum pressure.

Since 1916 the Pennsylvania Railroad has placed in service over five hundred locomotives operating at a steam pressure of 250 lb. These are engines of the 2–10–0 type used in work which requires them to maintain great tractive effort over protracted periods; they were consequently, for economy's sake, designed with limited cut-off; that is, their valve gear is so designed that no cut-off in excess of 50 per cent of the stroke may be attained, and the cylinders are proportioned with respect to the limited cut-off and the high pressure. When these locomotives were originated, 250 lb. was considerably in advance of usual pressures, and this pressure was adopted chiefly because of the limited cut-off. This use of moderately high pressure to attain cylinder economy by means of more favorable expansion ratios is one which has recently attracted much attention and gained much favor. The boilers of these Pennsylvania locomotives are of the usual extended wagon-top type with Belpaire fireboxes; the barrel plates are $1^1/_4$ in. thick and the boilers are otherwise strengthened for the high pressure; but they embody no other important departures from ordinary boiler design. Their superheat varies up to 280 deg.

About a year and a half ago the Lima Locomotive Works completed an experimental locomotive of the 2–8–4 type, called the A-1, which embodied various novel features of design. It is interesting in this connection, however, chiefly because it carries 240 lb. boiler pressure and has its cut-off limited to 60 per cent. There are no unusual features in the boiler design—at least none which were demanded by the high pressure. This engine was first placed in service on the Boston & Albany Railroad, and afterward used on various roads. The Lima Works has since built 25 similar locomotives for the Boston & Albany Railroad which carry the same pressure, and is now building 20 additional engines for this road. During the present year the Texas & Pacific Railroad has placed in service ten similar locomotives of the 2–10–4 type, which have boilers of the usual design carrying 250 lb. pressure. The Lima Works is also building for the Illinois Central Railroad 50 locomotives like the A-1, of the 2–8–4 type, carrying 240 lb. boiler pressure; and for the Pennsylvania Railroad it has under construction 25 locomotives of the 4–8–2 type which will carry 250 lb.

The highest pressure in a locomotive boiler of ordinary design of which we have knowledge is 285 lb. This pressure will be carried on an experimental turbine-driven locomotive being built by Beyer, Peacock & Company in England. It will weigh 143 tons and is expected to develop 2000 hp. The boiler is of the usual locomotive type with Belpaire firebox, steel firebox sheets, and steel tubes.

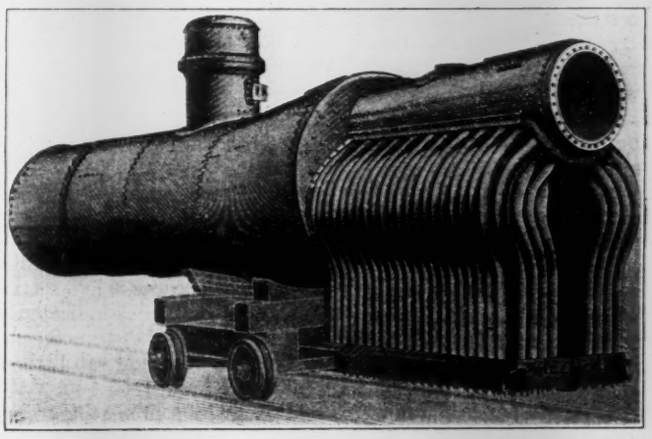

FIG. 2 BROTAN LOCOMOTIVE BOILER WITH SHORT COLLECTING DRUM
(In some designs the drum extends forward over the full length of the main boiler shell.)

The first locomotive boiler with a water-tube firebox was applied to a freight engine on the Austrian State Railways in 1901. It was designed by the chief engineer of that railway, Herr Brotan, and it is obviously the forerunner of the McClellon boiler, the boiler of the *Horatio Allen*, and that used on the high-pressure locomotive of the German Railways.

Until 1885 the maximum boiler pressure in use on the Austrian Railways was 150 lb., but at about that date then began to use higher pressures. Under 150 lb. boiler pressure the life of the copper firebox sheets was about 25 years, but as the pressure was gradually increased up to 240 lb. the life of these sheets became shorter until finally they had to be renewed every three or four years. These maintenance difficulties were aggravated by the bad feedwater in use on certain parts of the system, and by the fact that some of the coal had a very high sulphur content, which caused rapid deterioration of the copper side sheets and staybolt heads. This increase in the cost of maintenance appears to have been the chief reason for resorting to the water-tube construction of the Brotan design, rather than any desire to use extremely high pressures. In the records available to the authors the Brotan boiler does not appear to have been used for pressures in excess of 240 lb.

The general construction of the Brotan boiler is shown in Fig. 2. In this boiler a hollow ring takes the place of the usual mud ring. This ring is connected at the front to the bottom of the main boiler shell; from the ring rise a number of small water tubes which form the walls of the firebox and which are connected at the top to a collecting drum of small diameter. In one design the collecting drum is connected into the rear tube sheet of the main boiler shell; in another design the drum extends forward above the main boiler shell and is connected thereto by several short vertical sleeves.

After the preliminary experience with the Brotan boiler in 1901 it was applied to a considerable number of engines on the Austrian railways, and it was also tried on various other European railways, including those of Hungary, Russia, Switzerland, Prussia, and France. In recent years scores of locomotives with Brotan boilers have been placed in service on Austrian and Hungarian roads.

In 1916 the New York, New Haven & Hartford Railroad placed in service two Mikado-type locomotives with McClellon boilers carrying 180 lb. pressure. These boilers resemble in their design the Brotan boiler referred to above. Certain defects developed in these experimental locomotives and their removal and the development of the design was delayed by the death of the inventor, James M. McClellon. In 1920, however, these locomotives were modified in accordance with the experience previously gained and replaced in service. As a result of their satisfactory performance this railroad in 1924 placed the McClellon boiler on one of 10 Mountain-type locomotives ordered that year. More recently they have applied the same type of boiler on 10 additional new engines. All these engines, except the two first mentioned, carry a boiler pressure of 250 lb.

Fig. 1 and Figs. 3 to 6 show the construction of this boiler on New York, New Haven & Hartford locomotive No. 3500, the Mountain-type locomotive which was placed in service in 1924. Between it and the standard boiler the chief differences are in the construction of the firebox and the combustion chamber. Except for a small section below the firedoor all flat plate surfaces are eliminated from the firebox, their place being taken by water tubes which are 4 in. in diameter at the sides, and 2 in. in diameter on the back head. The mud ring is formed by a single hollow steel casting from which the water tubes rise to three drums of small diameter which form the top of the firebox. These three drums are flattened where they adjoin and are kept in connection along the flattened surfaces by means of screw rivets. Steel braces running between the mud ring and the upper drums relieve the water tubes of all stresses except those which arise from the steam pressure. The firedoor opening is in a section of combined water-leg and water-tube construction as indicated in Fig. 3. The plate shown in this view forms a part of the bracing and it carries at the same time some of the back head and cab fittings.

The combustion-chamber walls are also formed of 4-in. water tubes which connect the three upper drums with a circulating trough located at the bottom of the chamber and extending forward under the main boiler shell. The purpose of this circulating trough is to permit the circulation of water from the main boiler barrel to the firebox and the combustion chamber. It is riveted on the outside of the rear course of the main shell at the bottom; its front end extends ahead of the tube sheet and opens into the boiler through the shell, while the rear end is riveted to a flanged opening in the forward throat sheet as indicated in Fig. 6.[6]

The circulation in this boiler has proved to be excellent and the time required to fire it up is about two-thirds of the time usually required with the standard boiler. It can also be washed out in considerably less time than is required for the boiler of standard construction. Records kept since 1916 indicate that the cost of maintaining the McClellon boiler is roughly about one-half of the cost of maintenance of boilers of the usual type; and because of this great reduction in the amount of boiler work the locomotive has been more generally available for service.

As a result of their experience with the McClellon boiler, the motive-power officers of the New York, New Haven & Hartford Railroad are convinced of its suitability for use with high pressure, and of its economy of maintenance. As long as the water-tube firebox construction continues to be combined with standard construction of the main shell, the boiler pressure will, of course, continue to be limited by the design of the main boiler barrel, and this will probably not permit pressures much, if any, in excess of 300 lb. per sq. in.

After the ten Mountain-type locomotives above referred to were placed in service, extensive tests were made to compare the one equipped with the McClellon boiler (No. 3500) with one of the others of standard design (No. 3324). The two locomotives are substantially alike except as regards their boiler construction, steam pressure, and maximum cut-off. No. 3500 carries 250 lb. and has 70 per cent maximum cut-off, whereas No. 3324 carries 200 lb. pressure and has 80 per cent cut-off. The increase in maximum tractive effort of No. 3500 over No. 3324 amounted to 17.6 per cent. The steam per indicated horsepower-hour for the two engines was, respectively, 14.51 lb. and 15.52 lb., or a decrease of 6.5 per cent for locomotive No. 3500. The dry coal consumed per drawbar horsepower-hour was 2.50 lb. for the locomotive of the new design and 2.95 lb. for the standard machine, which is a saving of 15.2 per cent in favor of the new type.

It is understood that the American Locomotive Company is now building for the New York, New Haven & Hartford Railroad, additional locomotives equipped with McClellon boilers which will carry a steam pressure of 265 lb. It is also understood that the Baldwin Locomotive Works is building a high-pressure locomotive equipped with McClellon boiler.

If we accept the definition of the term "high pressure" previously suggested, the only high-pressure locomotive now in service on any American railroad is the Delaware & Hudson Company's locomotive No. 1400 which was placed in service in 1924 and named the *Horatio Allen*. It carries 350 lb. boiler pressure. This locomotive was designed by John E. Muhlfeld, consulting engineer for the Delaware & Hudson Company, and was bulit by the American Locomotive Company. It is of the Consolidation type, has 298,000 lb. weight on the drivers, and, without the booster with which the tender is equipped, it has developed in service a tractive force of 95,000 lb. with the cylinders in simple gear at 4 miles per hour, and 75,000 lb. at 5 miles per hour when working compound. The engine has cross-compound cylinders which are respectively 23½-in. and 41-in. in diameter, with a 30-in. stroke. Figs. 7, 8, and 9 represent the general design of this locomotive and of its boiler. The following detailed description is taken from the *Railway Age* for February 7, 1925.

The boiler represents a complete departure from customary locomotive design. The back head and rear tube-sheet connections of the firebox are both of similar construction. They are 9-in. water-leg headers composed of parallel stayed sheets, flanged and riveted together around the top and sides and secured to steel foundation castings at the bottom. Circular openings through each of these members near the lower corners receive water drums, 20 in. in inside diameter. These drums pass completely through both of the headers, and ports are cut through their shells in the header water spaces. The 30-in. steam drums at the top are secured to the front and back headers in the same manner. These drums are made in two courses, the front course fitting inside the rear course and extending 133 in. forward along the boiler shell. The front ends pass through a stayed saddle secured to the top of the boiler barrel, and ports through the drums and through the boiler shell provide for communication through the saddle between the drums and the boiler barrel. The ends of all four drums are closed with internally projecting heads and handhole covers. Four pipe connections lead out from the top of the boiler barrel between the forward extensions of the steam drums and connect alternately into the two drums, thus adding considerably to the freedom of communication between the boiler barrel, which is completely filled with water, and the drums, the upper parts of which constitute the steam space of the boiler. The front sheet of the forward firebox header is flanged outward to receive the back course of the two-course boiler barrel, which is 66⅛ in. in outside diameter. The inside sheet of this header is flanged inward to receive the firebox tube sheet.

The heating surfaces at the sides of the firebox are composed of 306 tubes, 102 of which are 2½ in. in diameter and 204 of which are 2 in. in diameter. These tubes are expanded into the top and bottom drums. It is thus evident that the stayed surfaces have been considerably reduced and are flat, parallel surfaces, with the exception of the small area of the firedoor flange. The drum and header type of construction, with the top headers carried forward and securely attached to the boiler barrel, also provides an extremely rigid structure.

Additional heating surface is provided in the firebox by ten 3-in. longitudinal water tubes which lie between the upper drums and connect the front and back stayed headers. There are also six 3½-in. arch tubes. The arch in this locomotive is unbroken from the tube sheet to the door sheet, thus completely dividing the unobstructed firebox volume into two parts. This directs the hot gases and flame outward at either side and up through the staggered rows of water tubes, thence inward to the combustion chamber volume above the arch and into the fire tubes.

Steam is taken from the tops of the forward sections of the steam drums. A welded collector pipe of ¼-in. steel, 6 in. in outside diameter and 79 in. long, is suspended from the top of each drum. The upper surface of each of these pipes is perforated with several rows of ½-in. holes, through which the steam enters, thus distributing the gathering of the steam over a large water surface and removing any tendency for a local surge of steam to lift the water. From the throttle the steam flows directly into the superheater header, which is mounted on a cast base over the top of the smokebox. The unit bolts are applied with the nuts at the top of the header, where they are accessible for tightening without opening the smokebox front. There are 42 superheater units, each of which consists of a single loop. The unit pipe leading from the saturated-steam header is twisted above the return

[6] A more detailed description of the construction of this boiler appears in the *Railway Mechanical Engineer*, March, 1926, pp. 143–150.

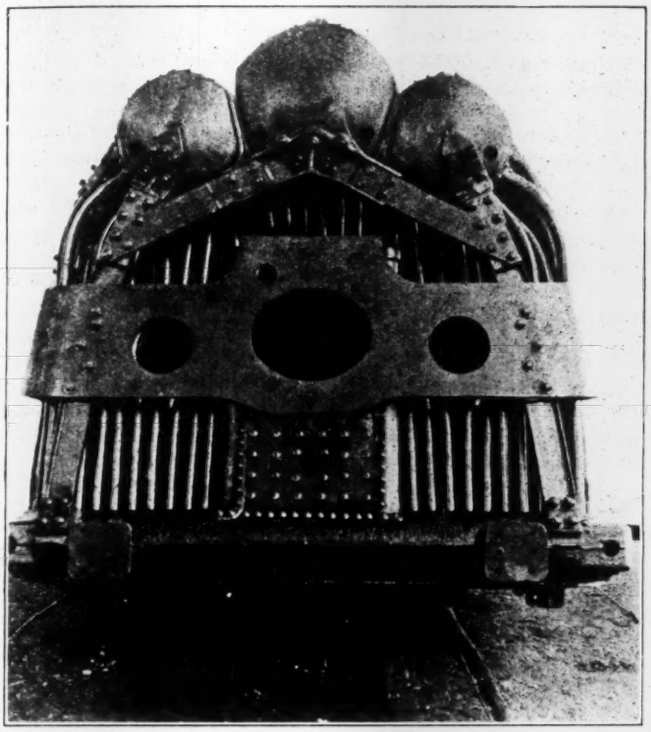

FIG. 3 A REAR VIEW OF THE FIREBOX OF THE MCCLELLON BOILER USED ON N. Y., N. H. & H. LOCOMOTIVE NO. 3500

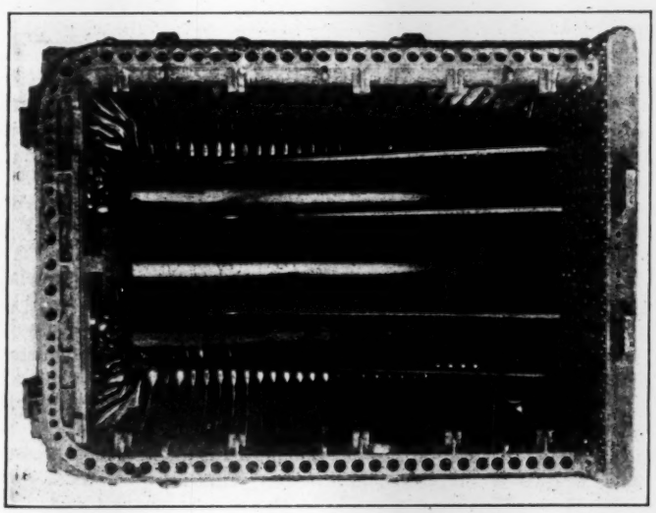

FIG. 4 INTERIOR OF THE FIREBOX OF THE MCCLELLON BOILER, SEEN FROM BELOW

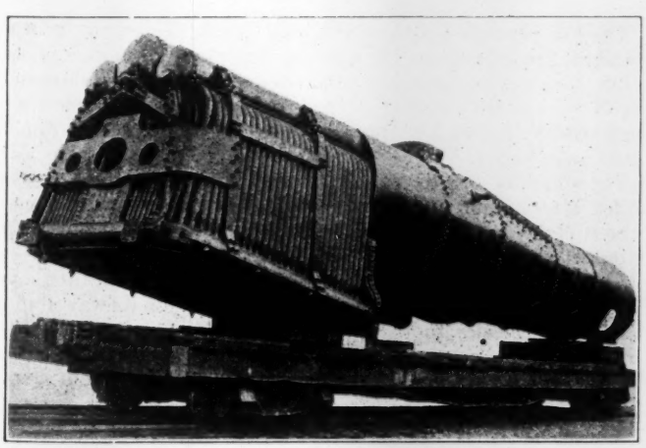

FIG. 5 THE COMPLETED MCCLELLON BOILER USED ON N. Y., N. H. & H. LOCOMOTIVE NO. 3500

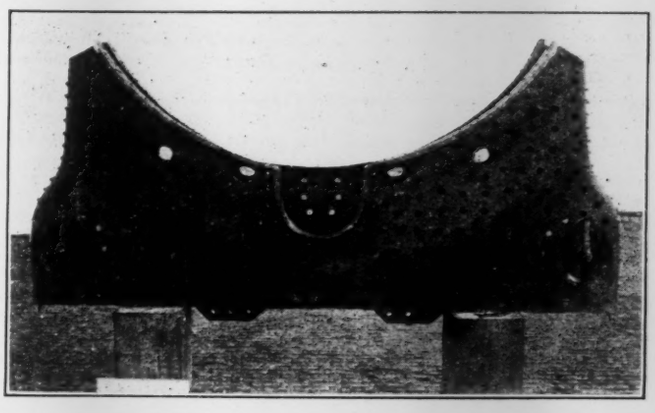

FIG. 6 THROAT CONSTRUCTION IN THE MCCLELLON BOILER SHOWING FLANGE FOR CONNECTION TO CIRCULATING TROUGH

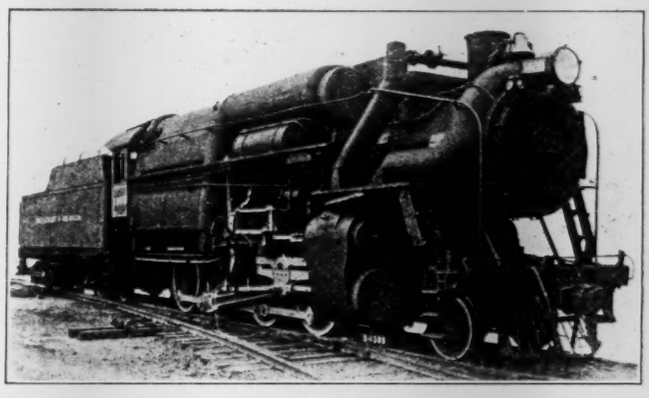

FIG. 7 DELAWARE & HUDSON COMPANY LOCOMOTIVE NO. 1400—THE "HORATIO ALLEN"

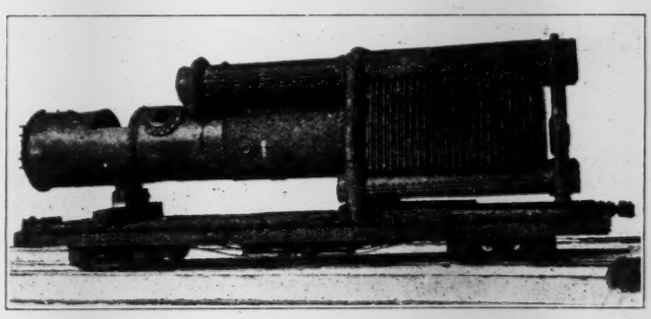

FIG. 8 THE COMPLETED BOILER FOR THE "HORATIO ALLEN"

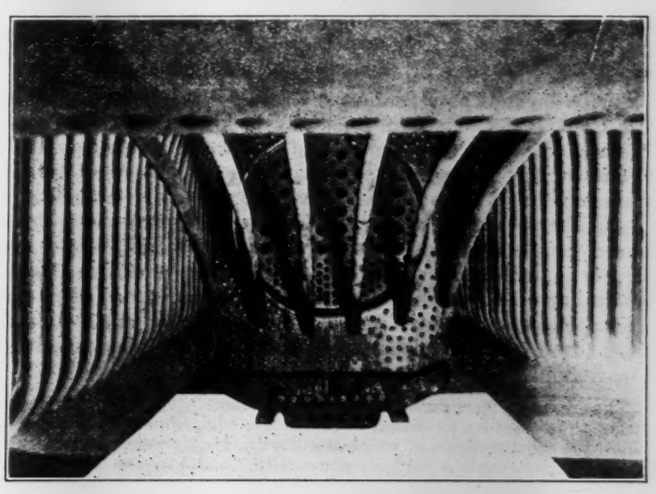

FIG. 9 THE INTERIOR OF THE FIREBOX OF THE "HORATIO ALLEN"

pipe in a spiral and the two pipes are threaded and welded into a cast-steel return bend which is located 12 in. from the back flue sheet. The whirling motion imparted to the saturated steam is designed to bring such moisture as the steam may contain into intimate contact with the unit surface, thus producing a more effective heat transfer. It also serves to equalize the expansion strains on the return-bend joints. Steam from the drifting valve passes through the superheater and thus serves to protect the units from overheating, when the throttle is closed. A flange on the right side of the superheater header leads the superheated steam into a branch-pipe connection to the high-pressure steam chest. In the design of this cylinder close attention has been given to providing unobstructed flow to and from the valve chamber.

Probably the outstanding difference in the proportions of the *Horatio Allen* as compared with locomotives of conventional design will be found in the distribution of the heating surface in the boiler. Out of a total heating surface of 3200 sq. ft., 1187 sq. ft., or 37 per cent, is located in the firebox. This is the result of the water-tube construction. . . . . Another factor of interest is the comparatively small amount of superheating surface, the total of which is 579 sq. ft. The purpose in this case, however, was to limit the maximum steam temperature to approximately 600 to 620 deg. fahr., and this temperature became the controlling factor in the design rather than the amount of superheat. With a boiler pressure of 200 lb. per sq. in., the superheater starts to build up the temperature of the steam from a saturated temperature of 388 deg. fahr. With the pressure increased to 350 lb., however, the saturated-steam temperature is raised to approximately 436 deg. and the amount of heat which can be imparted to the steam within a limit of 620 deg. is correspondingly reduced. Until it is determined what effect will be produced by a combination of high pressures and high temperatures, it was considered safer not to exceed the above maximum temperature.

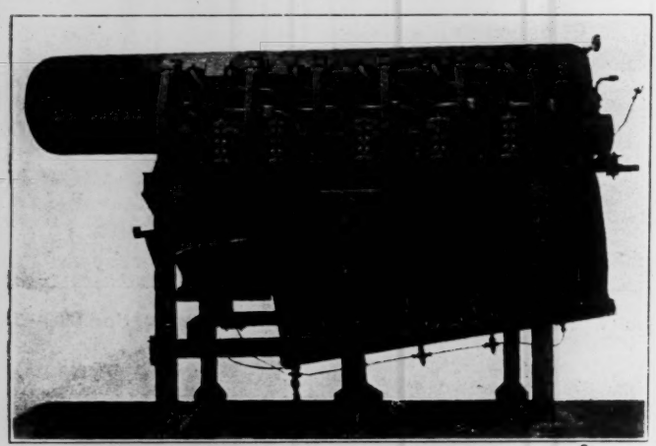

FIG. 10 HIGH-PRESSURE BOILER AND WATER-TUBE FIREBOX OF THE ULTRA-HIGH-PRESSURE LOCOMOTIVE OF THE GERMAN STATE RAILWAYS

When burning coal at the rate of 57.5 lb. per sq. ft. of grate per hour, this boiler has given an equivalent evaporation of 10.68 lb. of water per pound of coal and a combined efficiency of boiler and superheater of 75.8 per cent. The steam consumption of the main cylinders and the auxiliaries was 17.91 lb. per i.hp-hr. The dry coal used per drawbar horsepower-hour has proved to be 2.3 lb., which is equivalent to an overall efficiency of 8.02 per cent; that is, the locomotive has delivered as work at the drawbar 8.02 per cent of the heat units in the coal fired.

As a result of the satisfactory performance of the *Horatio Allen*, the Delaware & Hudson Company is now building the *John B. Jervis*, a locomotive of similar design which will carry, however, a boiler pressure of 400 lb., or 50 lb. more than the former.

Dr. Wilhelm Schmidt, whose name is closely associated with the use of superheated steam, especially in locomotive practice, also carried on, over a period of several decades investigations in connection with high-pressure steam. The results of these investigations have received much attention during recent years, and it appears likely that there will be further important developments along the lines suggested by them. Dr. Schmidt's work, made largely in connection with stationary boilers and engines, leads to many important conclusions some of which are particularly pertinent to locomotive practice. The following is a single quotation from a translation of a paper by O. H. Hartmann of the Schmidt'sche Heissdampf-Gesellschaft:

> The greatest advantages, however, are obtained by applying high-pressure steam to operate back-pressure reciprocating engines or back-pressure turbines, the exhaust steam of which is utilized. It is possible to obtain the same heat consumption per horsepower with a high-pressure exhaust engine working at 60 atmospheres initial pressure (852 lb.) and low back pressure as with a condensing engine working with the usual pressure, and all exhaust steam is still available for other purposes.

The original paper,[7] presented before the Verein deutscher Ingenieure, gives an extended account of the investigations made by Dr. Schmidt and his associates. Based on these investigations a locomotive which has been called an ultra-high-pressure locomotive was recently built for the German State Railways. This locomotive is a compound, three cylinder, 4–6–0, superheated-steam, high-speed engine, built by Henschel & Sohn, Cassel, Germany.

Steam at three different pressures is produced in this locomotive—at approximately 200, 850, and 1100 lb. per sq. in. The two lower pressures only are employed in the engine cylinders. The 1100-lb. steam is used in producing the 850-lb. steam. The single high-pressure cylinder of this locomotive receives steam at 850 lb. pressure from a special high-pressure boiler. The two low-pressure cylinders receive steam at approximately 200 lb. per sq. in. A fire-tube boiler of the usual construction produces 200-lb. steam which is mixed with the exhaust from the high-pressure cylinder to produce the steam supply for the low-pressure cylinders. Two superheaters, one for the 850-lb. steam, the other for the steam from the fire-tube boiler, are employed in order to permit the locomotive to take full advantage of superheating.

The method of producing the 850-lb.-pressure steam in the high-pressure boiler has brought about an important feature in the design of the locomotive. The 850-lb. steam is produced by passing the feedwater over heating coils containing steam at a pressure of from 1100 to 1300 lb. per sq. in. These heating coils, mounted in the high-pressure boiler, receive their steam from the tubes which make up the water-tube firebox of the locomotive. The firebox water tubes and the heating coils constitute a closed circulating system. By means of this arrangement much of the difficulty which might arise from boiler scale is avoided.

Fig. 10 shows the high-pressure boiler and the water-tube firebox. Fig. 11 presents a diagrammatic sketch and a drawing which show the arrangement of the principal parts of the locomotive. Fig. 12 is from a photograph of the complete locomotive. Brief descriptions and information concerning this locomotive have appeared in the technical press. The following more detailed description was furnished by the German State Railways.

The locomotive was built for two working pressures, 853 lb. per sq. in. (60 kg. per sq. cm.) working pressure being carried in the back end, or high-pressure boiler, and 199 lb. per sq. in. (14 kg. per sq. cm.) in the barrel of the normal or low-pressure boiler. The inner firebox is formed by water tubes the bottom ends of which reach into the water chambers of a hollow foundation ring, while their upper ends discharge into steam collectors. The system is filled with distilled water up to the tube ends in the steam collectors. From the latter, steam rises through vertical tubes to heating coils mounted in the high-pressure boiler, and the condensate falls back to the foundation-ring chambers through another set of tubes and there begins circulation anew. The heating of the high-pressure boiler is thus accomplished indirectly. The use of distilled water prevents the formation of scale in the firebox water tubes. The working pressure in the firebox tubes and the heating coils is 1100 to 1300 lb. per sq. in. (80 to 90 kg. per sq. cm.), and in the high-pressure boiler it amounts to 853 lb. per sq. in.

The low-pressure boiler, working at 199 lb. per sq. in., is of the standard fire-tube type. In order to reduce the formation of scale it has, besides the customary steam dome, a special feed dome with a grid over which the feedwater is sprayed. For the same reason the feedwater for the high-pressure boiler is pumped across from the main boiler barrel.

The steam at 850 lb. per sq. in. generated in the high-pressure boiler, after having undergone the superheating process in a small-tube superheater arranged in the lower flues of the fire-tube boiler, enters the steam chest of the high-pressure cylinder. The steam produced in the low-pressure boiler goes to another small-tube superheater located in the upper flues of this boiler. On its way from the superheater header to the two low-pressure cylinders the highly superheated low-pressure steam mixes with the exhaust steam from the high-pressure cylinder which at this point contains but a small

[7] Hochdruckdampf bis zu 60 Atmosphären in der Kraft- und Wärmewirtschaft, by O. H. Hartmann. *Zeitschrift des Vereines deutscher Ingenieure*, 1921, vol. 65, no. 26, p. 663.

amount of superheat. The resulting steam goes to the low-pressure cylinders at a temperature of about 570 deg. (300 deg. cent.); and after having performed its work in the cylinders, it is exhausted through the nozzle and smokestack in the usual way.

The low-pressure boiler is fed by a pump the delivery of which flows through a preheater; an injector of the current type is held in reserve. The high-pressure boiler gets its water supply from the low-pressure boiler by means of a pump, and there is also an injector for direct feeding of water from the tank to the high-pressure boiler.

Tests of this locomotive were to have been made during the past summer, but at the time this paper was prepared the results were not available. The designers expect it to save about 25 per cent in fuel as compared with standard locomotives; and, for like fuel consumption, to develop 35 or 40 per cent more work.

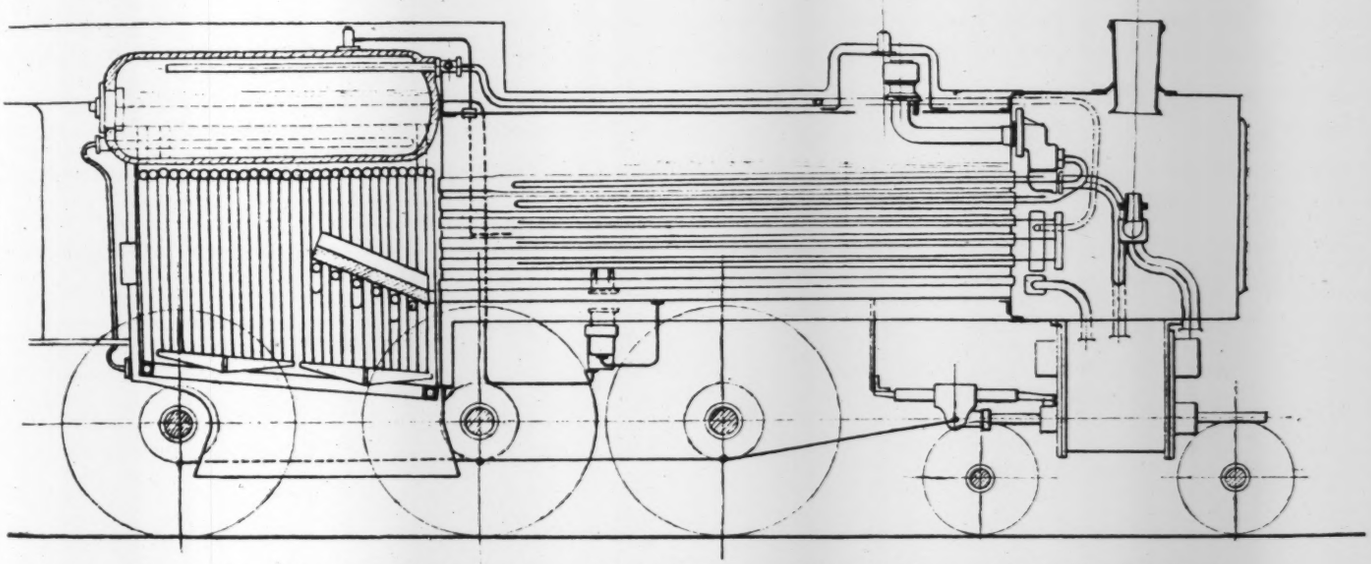

FIG. 11 DIAGRAMMATIC SKETCH SHOWING THE ARRANGEMENT OF THE PRINCIPAL ELEMENTS OF THE GERMAN STATE RAILWAYS' HIGH-PRESSURE LOCOMOTIVE

The principal dimensions of the ultra-high-pressure locomotive are:

Diameter of high-pressure cylinder	$11^{7}/_{16}$ in.	(290 mm.)
Diameter of low-pressure cylinders	$19^{11}/_{16}$ in.	(500 mm.)
Piston stroke	$24^{13}/_{16}$ in.	(630 mm.)
Diameter of driving wheels	6 ft. 6 in.	(1980 mm.)
Diameter of truck wheels	3 ft. $3^{3}/_{8}$ in.	(1000 mm.)
Wheelbase, rigid	15 ft. 5 in.	(4700 mm.)
Wheelbase, total	30 ft. 0 in.	(9150 mm.)
Working pressures	850 lb. per sq. in.	(60 kg. per sq. cm.)
	199 lb. per sq. in.	(14 kg. per sq. cm.)
Grate area	28 sq. ft.	(2.6 sq. m.)
Heating surface of firebox (internal)	211 sq. ft.	(19.7 sq. m.)
Heating surface of boiler	1525 sq. ft.	(141.7 sq. m.)
Heating surface of tubes (internal)	1313 sq. ft.	(122.0 sq. m.)
Heating surface of superheaters	974.3 sq. ft.	(90.5 sq. m.)
Weight empty	about 185,000 lb.	(84,000 kg.)
Weight in working order	about 200,000 lb.	(91,000 kg.)
Weight on drivers	about 132,000 lb.	(60,000 kg.)
Tractive force	26,500 lb.	(12,000 kg.)

EXPERIENCE IN STATIONARY PLANTS

High-pressure steam has been experimented with and employed in stationary practice to a much greater extent than in locomotives. The common employment of water-tube boilers and the use of condensers in stationary plants, together with the limiting conditions found in locomotive service, have naturally led to the greater development in stationary practice. A very brief recital of some of the results of experience in that field may be suggestive in the consideration of the use of high-pressure steam in locomotives.

Experimentally, and to a considerable extent commercially, various steam pressures have been used up to as high as 1500 lb. per sq. in. The use of steam pressure in the neighborhood of 1200 lb. per sq. in. has received attention both in this country and abroad. A plant with a capacity of 150,000 lb. of steam per hour, designed for a pressure of 805 lb. per sq. in., is now in process of erection. Numerous stationary plants are in operation which employ steam pressures ranging from 300 to 500 lb. per sq. in.

The use of high-pressure steam appears to have been accepted as the best practice in the design and operation of several large central power stations which have been built recently. Information about some of the advantages and disadvantages of high-pressure steam and touching upon some of the maintenance and other problems

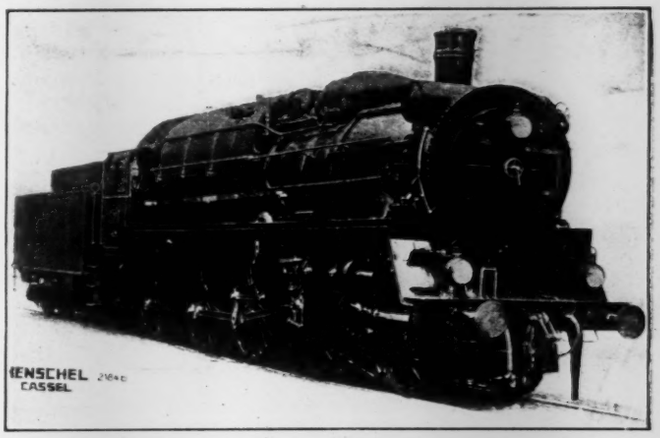

FIG. 12 THE GERMAN STATE RAILWAYS' HIGH-PRESSURE LOCOMOTIVE

which have been encountered in its use has been furnished by E. H. Tenney, Chief Engineer of Power Plants, Union Electric Light & Power Company, St. Louis, C. F. Hirshfeld, Chief of Research Department, Detroit Edison Company and Alexander D. Bailey, Superintendent of Generating Stations, Commonwealth Edison Company, Chicago. This information, from three of the largest modern central power stations in this country, is based upon practice with steam pressures of 330, 410, and 600 lb. per sq. in.

The Union Electric Light and Power Company has operated its Ashley Street Station for a number of years at 200 lb. steam pressure and 140 deg. superheat, and during the past two years has been operating the Cahokia Station at 330 lb. steam pressure and 250 deg. superheat. In the maintenance of piping, valves, and boilers it is difficult to differentiate between results that are due to pressure and those due to higher superheat. As nearly as differences due to pressure can be judged, it appears that boilers and large piping require but little more maintenance at the high-pressure plant. The

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chief difference is found in the fittings and valves, especially in the smaller sizes. These are of metal alloys adapted to the service, but even these alloys, at the pressure used, are subject to erosion, especially where the valve is cracked slightly instead of being wide open. Gaskets also give more trouble on small piping, and once a leak starts it increases rapidly. The service that seems to be most affected is that of drains of high-pressure steam lines; the various types of drain systems used have all required much more attention in the higher-pressure plant.

The most recent plant of the Detroit Edison Company operate with a steam pressure in the neighborhood of 410 to 420 lb. per sq. in. The steam temperature varies from 700 to 725 deg. fahr. Seamless tubing is used for the steam piping in this plant, and the joints in the steam line are of the ordinary Van Stone type with soft gaskets. There has been no trouble with boilers, piping, or turbines that could be attributed to either the pressure or temperature used. There has been some trouble with leakage at rolled joints in the superheaters and in the steel-tube economizers. The difficulties with the superheaters appear to be due to a combination of temperature stresses and imperfect design; they are being gradually removed. The difficulty with the economizer was due to imperfect design and has been eliminated.

At the Crawford Avenue Station of the Commonwealth Edison Company, which has now been in service about two years, the operating steam pressure is 600 lb. and the steam temperature 725 deg. fahr. The generating units at present installed vary in size from 50,000 to 75,000 kw. and the individual boilers have a maximum steaming capacity of 175,000 lb. of steam per hour at the stated pressure and temperature. While there were some troubles in the beginning which could be directly attributed to the high pressure or high temperature or to both, these were comparatively few; most of them had been anticipated and steps taken to avoid them. The steam piping is made up with Sargol welded joints which have given no trouble whatever, and the unusual expansions due to temperature have been satisfactorily taken care of with bends and sweeps. On the feed lines the joints are made with male and female flanges, using soft gaskets. The economizers gave considerable trouble due to leakage of the rolled joints; it was found that this was due, not altogether to pressure, but to expansion strains and to the sulphur in the flue gases which was active in corroding the economizer tubes and headers. The boiler fittings are all made unusually heavy. A new type of gage glass is used consisting of two heavy flat glasses mounted in a strong frame in such a way that the water is visible between them. These glasses are backed up on the water side with thin sheets of mica to prevent the rapid scoring of the glasses. Safety valves which it was anticipated would give trouble, have worked out very well; they have blown repeatedly, but have remained tight. Various valves on the boilers and their connections were specially designed for this service and, in general, have proved satisfactory. In general, it may be said that the troubles encountered have not been due mainly to the high pressure and temperature, but rather to the high capacity at which all this equipment is operated.

The foregoing statements, which are based upon large-scale operations, together with opinions expressed by practically all other recent users of high-pressure steam and by builders of equipment for this service, indicate the practicability of using high steam pressures and temperatures and of obtaining and maintaining equipment which will be satisfactory for pressures up to 800 lb. per sq. in. or higher, and for temperatures up to 700 to 750 deg. fahr. Experience in stationary practice has satisfactorily answered many of the questions which have arisen regarding the employment of high pressures and temperatures. The special problems which arise in locomotive practice due to condition peculiar to that service are being vigorously attacked. They appear to offer no insurmountable difficulties.

Theory of Milling Cutters

By N. N. SAWIN,[1] PILSEN, CZECHOSLOVAKIA

This paper presents an outline of a theory of milling cutters which, it is believed, will provide a basis for discussion. An attempt is made to find theoretical formulas for calculating the strength of mills and to determine their work.

FOR the right dimensioning of the spindle of a milling machine with regard to the work of the machine, it is necessary to know all forces acting upon the milling cutters. For rational standardization of milling cutters and their efficieney we must know how to calculate the work of the cutter.

For this problem we have the following values (see Fig. 1):

α = working angle of the tooth
φ = pitch angle of the tooth
β = spiral angle of the tooth
A = outside diameter of the cutter in inches
D = diameter of the cutter holder where the maximum bending moment takes place, in inches
l = distance between the center of resultant pressure of the chips and the place of maximum bending moment, in inches
z = number of teeth of the cutter
d = depth of cut in inches
h = width of cut in inches
f = feed, in. per min.
t = varying thickness of the chip in inches
δ = milling angle at given moment
n = speed of cutter, r.p.m.
K = cutting coefficient of material under consideration, lb. per sq. in.
F = strength of material to be cut, lb. per sq. in.
S = safe stress of cutter material for bending, lb. per sq. in.
M_t = torsional moment in in-lb.
Hp. = effective power of the cutter in horsepower
M_b = bending moment of the cutter in in-lb.
M_c = combined bending and torsional moment in in-lb.

Case I—Plain Cutter with Straight Teeth, One Tooth Working

To make the task easier, we shall first consider the simple case of a plain milling cutter with straight teeth, and continue up to the most complicated case of an end mill with spiral teeth.

To start the discussion of the action of a milling cutter, imagine a plain milling cutter with straight radial teeth taking a cut over a piece of work of which the width is less than the length of the cutter. To simplify the discussion still further, imagine the cutter working with only one tooth. This means that the working angle of the tooth, α, is smaller than its pitch angle, φ; that is, $\alpha < \varphi$. Spiral angle $\beta = 90°$.

Considering Fig. 1, we find that

$$\cos \alpha = 1 - \frac{2d}{A}$$

$$\alpha = \text{arc cos} \left(1 - \frac{2d}{A}\right) \quad [1]$$

the pitch angle of the tooth is represented by

$$\varphi = \frac{2\pi}{z} \quad [2]$$

Each point of the cutting edge of the cutter describes a trajectory curve, which is called an abridged cycloid.

The thickness of the chip is not interrupted and grows from zero, at the point where the cutter tooth enters the material, to t (max.), when the tooth leaves the work.

With sufficient accuracy we may write

$$t = \frac{f}{nz} \sin \delta \quad [3]$$

$$t \text{ (max.)} = \frac{f}{nz} \sin \alpha$$

in which f/nz is the feed for one tooth of the cutter. The section of the chip varies, therefore, from 0 to a maximum of $h \frac{f}{nz} \sin \alpha$.

It is clear, then, that the strain on the cutter and on the different parts of the milling machine will vary with the thickness of the chip.

The cutter will, during one revolution, receive z shocks; these occurring when the teeth leave the work. All forces acting upon

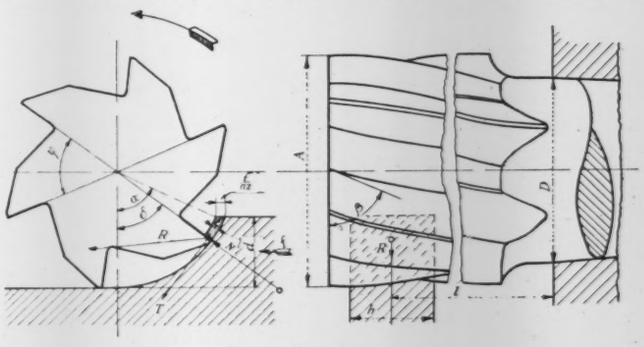

Fig. 1

the cutter will resolve into two components running in two main directions, namely, tangential, T, and normal, N. The tangential component runs in the direction of a tangent to the cutter and the normal component runs through the axis of the cutter. The tangential component is really the pressure of the chip on the front of the tooth and is equal to the product of the cross-section of the chip and the cutting coefficient K. This is represented by the equation

$$T = Kth = \frac{Kfh}{nz} \sin \delta \quad [4]$$

The normal component N is the normal pressure of the chip upon the cutting edge of the cutter.

The fundamental assumption on which the theory rests is that the normal component is equal to the tangential component; that is to say,

$$N = T$$

Assuming an ideal cutting edge without land and an enormous circumferential velocity of the cutter, that is, the cutting velocity $= \infty$, then we may figure $N = 0$.

In fact, each cutting edge has land, which comes in contact with the metal and causes friction. In case of absence of land, it would form after a few revolutions.

The circumferential cutting speed is seldom in excess of 160 ft. per min.

The torsional moment is represented by the expression

$$M_t = T \frac{A}{2}$$

To obtain the maximum value of T, make $\delta = \alpha$, when

$$T \text{ (max.)} = \frac{Kfh}{nz} \sin \alpha$$

and

$$M_t \text{ (max.)} = \frac{Kfh}{nz} \frac{A}{2} \sin \alpha \quad [5]$$

[1] Research Engineer, Skoda Works.

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The power necessary for cutting is represented by

$$\text{Hp.} = \frac{M_t\, 2\pi n}{12 \times 33\,000} = \frac{0.159\, n M_t}{10^4} \quad [6]$$

In addition to the torsional moment, a bending moment M_b acts upon the cutter, and this is determined by product of resultant R and the distance l. R is the resultant of the normal and tangential force.

$$R = \sqrt{N^2 + T^2} = T\sqrt{2} \quad [7]$$

$$M_b = lR = \sqrt{2}\, lT = 1.4142\, lT \quad [8]$$

No axial pressure is exerted upon the cutter. Combined moment is given by the relation:

$$M_c = 0.35\, M_b + 0.65\, \sqrt{M_b^2 + (\eta M_t)^2} \quad [9]$$

For practical purposes, $\eta = 1$.

The section modulus at the point of maximum bending moment is represented by

$$Z = \frac{\pi D^3}{32} \quad [10]$$

Supposing

$$Z \geqq \frac{M_c}{S}$$

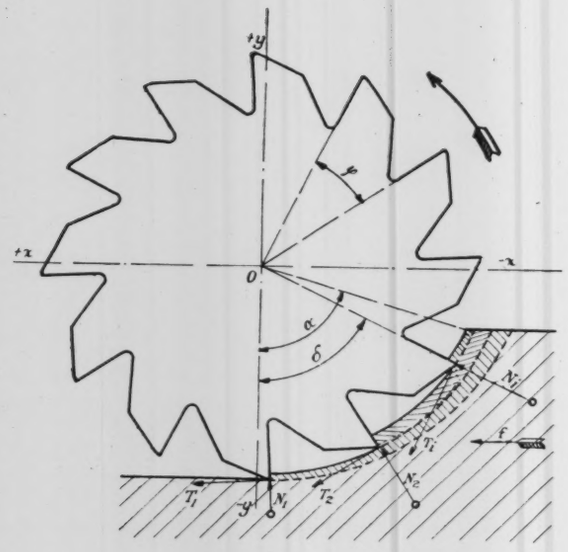

Fig. 2

we obtain

$$D \geqq \sqrt[3]{\frac{32\, M_c\ (\text{max.})}{\pi S}} \quad [11]$$

Assuming a safe bending stress of $S = 12{,}000$ lb. per sq. in. regardless of whether it is a shell mill or not,

$$D \geqq 0.0947\, \sqrt[3]{M_c\ (\text{max.})}$$

We can check the strength of the tooth of the cutter by considering the greatest width of the tooth. We obtain always satisfactory results. We may claim that the strength of the tooth depends particularly upon the quality of steel and its heat treatment.

The shape of tooth and the chip space are constructed according to generally known rules.

Example I. $A = 1.5$; $D = 1.75$; $z = 10$; $n = 200$; $d = 0.11$; $h = 2.4$; $f = 4$; $l = 4$; material to cut, medium cast iron; $S = 12{,}000$.

$\cos \alpha = 0.85$	$M = 748$
$\alpha = 32°$	Hp. $= 2.4$
$\alpha = 36°$	$M_b = 5640$
t (max.) $= 0.00106$	$M_c = 5697$
$K = 392{,}000$*	$D \geqq 1.69$
$T = 997$	

Case II—Plain Cutter with Straight Teeth, Several Teeth Working Simultaneously

Let us consider a case where several teeth are working simultaneously. The teeth are radial as in Fig. 2. In this case $\alpha > \varphi$ and $\beta = 90°$. The number of teeth working at a given time is $\kappa = \alpha/\varphi$. Let the tangential forces be represented by T_1, T_2, T_3, etc. As before, we may assume the tangential forces to be equal to the normal forces: $T_1 = N_1$; $T_2 = N_2$; ..... $T_i = N_i$.

The torsional moment acting upon the cutter is the sum of the torsional moments acting upon each tooth, or

$$M_t = \sum_1^{\kappa} M_{it}$$

Therefore

$$M_{it} = \frac{A}{2}\, T_i$$

$$T_i = \frac{Kfh}{nz} \sin \delta \quad [4a]$$

$$M_t = \frac{Kfh}{nz}\, \frac{A}{2} \sum_1^{\kappa} \sin \delta \quad [5a]$$

and the power necessary for rotating the cutter is represented by

$$\text{Hp.} = \frac{0.159\ nM_t}{10^4} \quad [6]$$

To determine the bending moment of all forces, all tangential and normal forces are projected in the direction of the x- and y-axes. Then

$$X = T_i \cos \delta + N_i \sin \delta = T_i\, (\cos \delta + \sin \delta)$$

$$Y = N_i \cos \delta - T_i \sin \delta = T_i\, (\cos \delta - \sin \delta)$$

The resultant forces in the directions of the x- and y-axes are:

$$X = \sum_1^{\kappa} X_i = \sum_1^{\kappa} T_i\, (\cos \delta + \sin \delta)$$

$$= \frac{Kfh}{nz} \sum_1^{\kappa} \sin \delta\, (\cos \delta + \sin \delta) \quad [12]$$

$$Y = \sum_1^{\kappa} Y_i = \sum_1^{\kappa} T_i\, (\cos \delta - \sin \delta)$$

$$= \frac{Kfh}{nz} \sum_1^{\kappa} \sin \delta\, (\cos \delta - \sin \delta) \quad [13]$$

The resultant of all X and Y forces is

$$R = \sqrt{X^2 + Y^2} \quad [14]$$

and the bending moment then is

$$M_b = lR \quad [8]$$

The combined bending moment and conditions for the strength of the shank can be obtained according to equations which have been developed for the first case.

In this case the cutter suffers shocks, because the pressure is suddenly released at the moment the tooth leaves the work. But the shocks are not as great as in the first case, where each tooth of the cutter leaves the work before the following tooth comes into engagement. Maximum strain on the cutter will take place at the moment the first tooth is about to leave the material, that is, when $\delta = \alpha$.

Minimum strain on the cutter takes place immediately after the tooth leaves the material, or when $\delta = \alpha - \varphi$.

These extreme values of the angle δ determine the extent of strain on the cutter.

* For medium cast iron, $K = \dfrac{40{,}000}{\sqrt[3]{t\ (\text{max.})}} = 392{,}000$.

Example II. $A = 3.15$; $D = 2$; $z = 18$; $n = 100$; $\alpha = 0.44$; $h = 1.57$; $f = 1.57$; $l = 3.94$; $S = 12{,}000$; $F = 50{,}000$ (steel).

$$\cos \alpha = 0.72$$

$$\alpha = 44°$$

$$\varphi = 20°$$

$$\kappa = \frac{44}{20}; \quad \kappa > 2$$

$$t \text{ (max.)} = 0.0006$$

$$K = 574{,}000\dagger$$

$$\frac{Kfh}{nz} = 786$$

$$M_t = \frac{Kfh}{nz} \frac{A}{2} \sum_1^s \sin \delta = 786 \frac{3.15}{2} (\sin 44° + \sin 24° + \sin 4°) = 1448$$

$$\text{Hp.} = 2.33$$

$$X = \frac{Kfh}{nz} \Big[\sin 44° (\cos 44° + \sin 44°) + \sin 24° (\cos 24° + \sin 24°) + \sin 4° (\cos 4° + \sin 4°) \Big] = 1.59 \frac{Kfh}{nz}$$

$$Y = \frac{Kfh}{nz} \Big[\sin 44° (\cos 44° - \sin 44°) + \sin 24° (\cos 24° - \sin 24°) + \sin 4° (\cos 4° - \sin 4°) \Big] = 0.29 \frac{Kfh}{nz}$$

$$R = \frac{Kfh}{nz} \sqrt{1.59^2 + 0.29^2} = 1270$$

$$M_t = 5004$$

$$M_e = 5137$$

$$D \geqq 0.0947 \sqrt[3]{5137}; \quad D \geqq 1.64$$

The effective power fluctuates between 0.96 and 2.33 hp., and we have such fluctuations as $100 \times 18 = 1800$ per minute.

CASE III—CUTTER WITH SPIRAL TEETH

Let us assume a more complicated case of milling, such as is often met in practice; that is, the case of a cutter with spiral teeth. In this case the cutting edge of each tooth will not engage over the entire length at once, but gradually, and will leave the work in the same manner. When cutters with spiral teeth are used one must always consider the axial pressure of the chip. The axial pressure should not pull the cutter out from its seat. A right-hand cutter must have a left-hand spiral and a left-hand cutter must have a right-hand spiral. Right-hand cutting is said to exist when the direction of rotation of the cutter is clockwise (looking at the cutter from the operator's standpoint).

The number of teeth in action κ depends in this case not only on the ratio α/φ but also on the depth d of the cut and on the spiral angle β of the cutter, as shown in Fig. 3, in which the circumference of the cutter is developed into a flat surface. The teeth enter the cutting area *abcd* gradually, and the number of the teeth in action varies periodically. For instance, at one moment two teeth are working, as 2-2 and 3-3; at the next moment three teeth, as 1′-1′; 2′-2′; 3′-3′, are working. When entering, the angle = 0, and when leaving, the angle α is realized.

The difference between the straight-tooth cutter and spiral cutter is that in the straight-tooth cutter the tooth pressure and the size of the chip are constant at all times, while in a spiral cutter this pressure varies according to engagement and the thickness of the chip varies with it.

There is still another difference between the two types of cutters. The maximum effort in a straight-tooth milling cutter occurs at the moment the tooth leaves the work. In a spiral-tooth cutter the effort is continuous, growing from zero to a certain maximum, remaining for a while, and then decreasing again to zero. Accordingly, shocks are avoided, but a periodical variation of effort still exists; however, its extent is much smaller than in a straight-tooth milling cutter.

In Fig. 3, β is the lead angle of the spiral and γ_h the cutting angle corresponding with maximum h. In this case we shall have for the length s of the tooth

$$s = \frac{h}{\sin \beta}$$

in which

$$h = \gamma_h \frac{A}{2} \tan \beta$$

or

$$\gamma_h = \frac{2h}{A \tan \beta} \quad \ldots\ldots [15]$$

and

$$\frac{A}{2} \tan \beta = \frac{h}{\gamma_h} \quad \ldots\ldots [16]$$

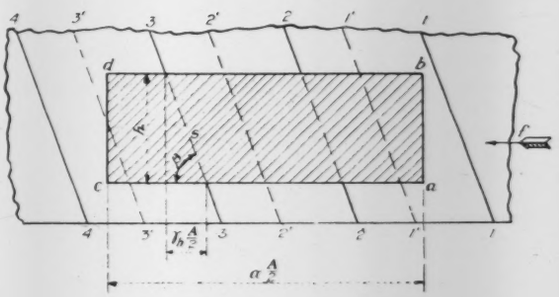

FIG. 3

During transit from point s with cutting angle δ (see Fig. 4) to the nearest point, the following equation will exist:

$$ds = \frac{dh}{\sin \beta}$$

but as

$$hd = \frac{A}{2} \tan \beta \, d\delta$$

we may write

$$ds = \frac{A}{2} \frac{d\delta}{\cos \beta}$$

The thickness of the chip t at point s will be

$$t = \frac{f}{nz} \sin \beta \sin \delta \quad \ldots\ldots [17]$$

$$t \text{ (max.)} = \frac{f}{nz} \sin \beta \sin \alpha \quad \ldots\ldots [18]$$

The cross-section of the chip will be

$$tds = \frac{A}{2} \tan \beta \frac{f}{nz} \sin \delta \, d\delta$$

According to Equation [16] we can write

$$tds = \frac{f}{nz} \frac{h}{\gamma_h} \sin \delta \, d\delta \quad \ldots\ldots [19]$$

The external forces which act in the line ds will be a tangential force dT'_i and a normal force dN'_i. The first force is at right angles to the face of the tooth and is equal to the cross-section of the chip multiplied by the cutting factor K.

$$dT'_i = Ktds = \frac{Kfh}{nz} \frac{1}{\gamma_h} \sin \delta \, d\delta \quad \ldots\ldots [20]$$

The normal pressure dN'_i has a direction perpendicular to the surface of the cutter, and again the assumption that both forces are equal may be made, or that $dN'_i = dT'_i$.

If the clearance angle of the tooth is λ, in other words, when the cutting angle is equal to $90 - \lambda$, the force dT'_i resolves itself in two

† For steel. $K = F \frac{1.8}{\sqrt[4]{t \text{ (max.)}}} = 50{,}000 \frac{1.8}{\sqrt[4]{0.0006}} = 574{,}000.$

components, one in the direction of the tangent, $dT'_i \cos \lambda$, and the second in a radial direction, $dT'_i \sin \lambda$.

Projecting the element of the force dT'-dN' on a system of coördinates x, y, which are at right angles to the axis of the cutter and also to the axis z, which is parallel with the axis of the cutter, we obtain:

Tangential Force:

$$dT_i = dT'_i \cos \lambda \sin \beta \ldots\ldots\ldots\ldots [21]$$

Normal Force:

$$dN_i = dN'_i - dT'_i \sin \lambda \sin \beta = dT'_i (1 - \sin \lambda \sin \beta) \ldots [22]$$

Axial Force:

$$dV_i = dT'_i \cos \beta \ldots\ldots\ldots\ldots\ldots [23]$$

The torsional moment then will be

$$d M_{it} = \frac{A}{2} dT_i$$

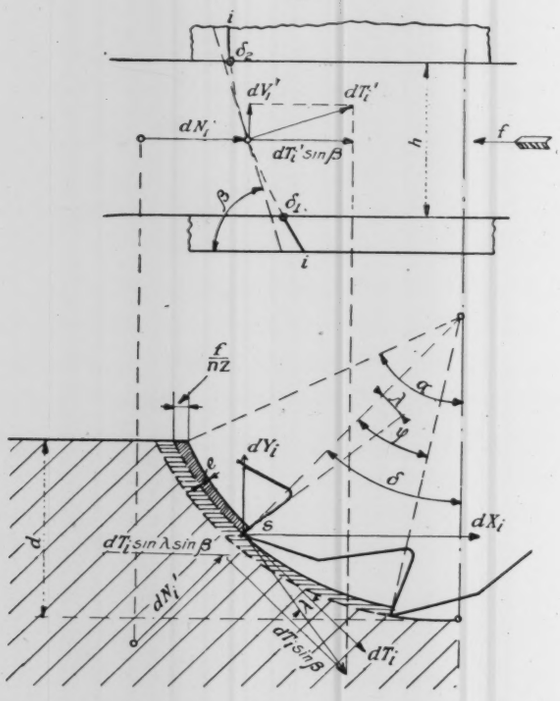

Fig. 4

which can be developed into

$$dM_{it} = \frac{Kfh}{nz} \frac{A}{2} \cos \lambda \sin \beta \frac{1}{\gamma_h} \sin \delta \, d\delta \ldots\ldots [24]$$

To obtain M_{it} we must integrate within the limits of δ_1 to δ_2, which are the minimum and maximum cutting angles. In other words, δ_1 is the cutting angle when the cutter leaves the material, and δ_2 the angle when the cutter enters it.

$$M_{it} = \frac{Kfh}{nz} \frac{A}{2} \cos \lambda \sin \beta \frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin \delta \, d\delta \ldots\ldots [25]$$

Designating

$$\frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin \delta \, d\delta = - \frac{\cos \delta_2 - \cos \delta_1}{\gamma_h} \text{ by } B_i \ldots\ldots [26]$$

then

$$M_{it} = \frac{Kfh}{nz} \frac{A}{2} \cos \lambda \sin \beta \, B_i \ldots\ldots\ldots [27]$$

The torsional moment M_t for the cutter is equal to the algebraic sum of the torsional moments of all teeth which are simultaneously in action, and is represented by the equation

$$M_t = \sum_1^\kappa M_{it} \ldots\ldots\ldots\ldots [28]$$

Accordingly, for the calculation of the torsional moment, one must solve the integral for all teeth simultaneously in action and then find the minimum and maximum angles and the maximum and minimum strains of the cutting teeth in their different positions.

This task is easier to perform graphically. The whole period of engagement, $\varphi = \frac{360}{z}$, is divided into several equal intervals, for instance, 5 deg.

Practically, it is not in error to assume that maximum strain corresponds with the entrance of one tooth into the end point of the zero line of cutting, *ab* (see Fig. 3); for spiral teeth, as shown on Fig. 3, it is point *a;* for reverse direction of spiral, it is point *b*.

For the power of the milling cutter we have, as before,

$$\text{Hp.} = \frac{0.159 \; nM_t}{10^4} \ldots\ldots\ldots\ldots [6]$$

The bending moment M_b which acts upon the cutter may be obtained as a sum of all bending moments, of resultant R of all forces acting in plane x-y, and of the resultant V_i of all axial forces (see Fig. 4), and is represented by the equation

$$M_b = M_{Rb} \mp M_{Vb} \ldots\ldots\ldots\ldots [29]$$

The moment M_{Vb} is negative when the axial force has a tendency to pull the cutter out of its socket.

Further,

$$M_{Rb} = lR$$

$$M_{Vb} = V \frac{A}{2}$$

From Equations [20], [23], and [26] we obtain

$$V = \sum_1^\kappa V_i = \cos \beta \sum_1^\kappa \left(\int_{\delta_1}^{\delta_2} dT'_i \right) = \frac{Kfh}{nz} \cos \beta \sum_1^\kappa B_i \ldots [30]$$

and

$$R = \sqrt{X^2 + Y^2} \ldots\ldots\ldots\ldots [31]$$

X and Y are resultant forces of all projected forces on the axes x and y.

$$X = \sum_1^\kappa X_i$$

$$Y = \sum_1^\kappa Y_i$$

$$X_i = \int_{\delta_1}^{\delta_2} X_i$$

$$Y_i = \int_{\delta_2}^{\delta_1} dY_i$$

$$dX_i = dT_i \cos \delta + dN_i \sin \delta$$
$$= dT'_i \cos \lambda \sin \beta \cos \delta + dT'_i (1 - \sin \lambda \sin \beta) \sin \delta$$

$$dV_i = dN_i \cos \delta - dT_i \sin \delta$$
$$= dT'_i (1 - \sin \lambda \sin \beta) \cos \delta - dT'_i \cos \lambda \sin \beta \sin \delta$$

After substitution,

$$X_i = \frac{Kfh}{nz} \cos \lambda \sin \beta \frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin \delta \cos \delta \, d\delta + \frac{Kfh}{nz} (1 - \sin \lambda \sin \beta) \frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin^2 \delta \, d\delta$$

$$Y_i = \frac{Kfh}{nz} (1 - \sin \lambda \sin \beta) \frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin \delta \cos \delta \, d\delta - \frac{Kfh}{nz} \cos \lambda \sin \beta \frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin^2 \delta \, d\delta$$

Designating

$$\frac{1}{\gamma_h} \int_{\delta_1}^{\delta_2} \sin \delta \cos \delta \, d\delta = \frac{\sin^2 \delta_2 - \sin^2 \delta_1}{2\gamma_h} \text{ by } C_i \ldots [32]$$

$$\frac{1}{\gamma_k}\int_{\delta_1}^{\delta_2}\sin^2\delta\,d\delta = \frac{-\,{}^1/_4\,(\sin 2\delta_2 - \sin 2\delta_1) + {}^1/_2\,(\delta_2 - \delta_1)}{\gamma_k}$$

by E_i ..... [33]

and

$$\frac{Kfh}{nz} \text{ by } Q \text{ ..... [34]}$$

we obtain

$$X_i = Q\,[\cos\lambda\sin\beta\,C_i + (1 - \sin\lambda\sin\beta)\,E_i]$$

$$Y_i = Q\,[(1 - \sin\lambda\sin\beta)\,C_i - \cos\lambda\sin\beta\,E_i]$$

$$X = Q\,[\cos\lambda\sin\beta\sum_1^\kappa C_i + (1 - \sin\lambda\sin\beta)\sum_1^\kappa E_i]$$

$$Y = Q\,[(1 - \sin\lambda\sin\beta)\sum_1^\kappa C_i - \cos\lambda\sin\beta\sum_1^\kappa E_i]$$

After substituting these values in Equation [31], we obtain

$$R = Q\sqrt{\left[(\cos\lambda\sin\beta)^2 + (1 - \sin\lambda\sin\beta)^2\right]\left[(\sum_1^\kappa C_i)^2 + (\sum_1^\kappa E_i)^2\right]}$$

The bending moment, according to Equation [29], is

$$M_b = Q\left\{ l\sqrt{\left[(\cos\lambda\sin\beta)^2 + (1 - \sin\lambda\sin\beta)^2\right]\left[(\sum_1^\kappa C_i)^2 + (\sum_1^\kappa E_i)^2\right]} \mp \frac{A}{2}\cos\beta\sum_1^\kappa B_i\right\} \text{ ..... [35]}$$

and the combined moment, as before, is

$$M_c = 0.35\,M_b + 0.65\sqrt{M_b^2 + M_t^2} \text{ ..... [9]}$$

and

$$D \geq \sqrt[3]{\frac{32\,M_c}{\pi S}}$$

To simplify the equations further let

$$\cos\lambda\sin\beta = u \text{ ..... [36]}$$

$$1 - \sin\lambda\sin\beta = w \text{ ..... [37]}$$

After substituting we obtain equations for a cutter with spiral teeth as follows:

$$M_t = Q\frac{A}{2}u\sum_1^k B_i \text{ ..... I (28)}$$

$$\text{Hp.} = \frac{0.159\;nM_t}{10^4} \text{ ..... II (6)}$$

$$V = Q\cos\beta\sum_1^\kappa B_i \text{ ..... III (30)}$$

$$M_b = Q\left\{ l\sqrt{(u^2 + w^2)\left[(\sum_1^\kappa C_i)^2 + (\sum_1^\kappa E_i)^2\right]} \mp \frac{A}{2}\cos\beta\sum_1^\kappa B_i\right\} \text{ .... IV (35)}$$

$$M_c = 0.35\,M_b + 0.65\sqrt{M_b^2 + M_t^2} \text{ ..... V(9)}$$

$$D \geq \sqrt[3]{\frac{32\,M_c}{\pi S}} \text{ ..... VI(11)}$$

$$\sum_1^\kappa B_i r = \frac{1}{\gamma_k}\sum_1^\kappa (\cos\delta_1 - \cos\delta_1)$$

$$\sum_1^\kappa C_i = \frac{1}{2\gamma_k}\sum_1^\kappa (\sin^2\delta_1 - \sin^2\delta_2)$$

$$\sum_1^\kappa E_i = \frac{1}{4\gamma_k}\sum_1^\kappa [(\sin 2\delta_1 - \sin 2\delta_2) + 2\,(\delta_2 - \delta_1)]$$

$$\gamma_k = \frac{2h}{A\tan\beta}$$

$$u = \cos\lambda\sin\beta$$

$$w = 1 - \sin\lambda\sin\beta$$

$$Q = \frac{Kfh}{nz}$$

These theoretically developed equations were checked on different milling machines with roughing and finishing cutters of high-speed steel upon different materials, and the results of tests were in harmony with results obtained by calculations.

Tests with end mills of chrome-tungsten steel show that the cutter breaks in the section of maximum bending moment at a bending stress F_b of 150,000 to 170,000 lb. per sq. in. Therefore we may take as the safe stress for these mills, S = 12,000 lb. per sq. in. Using shell mills for arbors of ordinary tool steel (not hardened), a safe stress of S = 12,000 lb. per sq. in. may also be taken.

It must be borne in mind that the cutting coefficient for milling chips of small thickness up to 0.0125 in. is far greater than that for turning. In turning practice the cutting coefficient K for steel can be assumed as approximately 2.5 to 3.5 times greater than the coefficient of tension. For milling, this coefficient should be taken with regard to the maximum thickness of the chip, t (max.) $= \frac{f}{nz}\times \sin\alpha\sin\beta$, and with regard to the strength of material to be cut.

A series of tests has proved that for practical purposes it is sufficient to assume

$$K = F\frac{1.8}{\sqrt[4]{t\,(\text{max.})}} \text{ for steel}$$

$$= \frac{28{,}000}{\sqrt[3]{t\,(\text{max.})}} \text{ for soft cast iron}$$

$$= \frac{40{,}000}{\sqrt[3]{t\,(\text{max.})}} \text{ for medium cast iron}$$

$$= \frac{56{,}000}{\sqrt[3]{t\,(\text{max.})}} \text{ for hard cast iron}$$

Example III (Fig. 5). A = 1.575; D = 1.575; z = 9; β = 70°; λ = 10°; n = 200; d = 0.118; h = 3.15; f = 3.937; l = 3.937; S = 12,000; F = 66,000 (steel).

$$\cos\alpha = 0.85$$

$$\alpha = 32°$$

$$\varphi = 40°$$

$$\text{arc } \gamma_k = \frac{2\cdot 3.15}{1.575\tan 70°} = 1.45;\ \gamma_k = 83°$$

$$t\,(\text{max.}) = 0.0011$$

$$K = 652{,}000‡$$

$$Q = \frac{Kfh}{nz} = 4492$$

$$u = 0.925$$

$$w = 0.837$$

$$\sum_1^\kappa B_i = \frac{1}{1.45}(\cos 0° - \cos 4° + \cos 0° - \cos 32° + \cos 0° - \cos 32°) = 0.21$$

$$\sum_1^\kappa C_i = \frac{1}{2\cdot 1.45}(\sin^2 4° - \sin^2 0° + \sin^2 32° - \sin^2 0 + \sin^2 32° - \sin^2 0°) = 0.20$$

$$\sum_1^\kappa E_i = \frac{1}{4\cdot 1.45}\left[(\sin 0° - \sin 8° + \sin 0° - \sin 64° + \sin 0 - \sin 64°) + \frac{2\pi}{180}(4 - 0 + 32 - 0 + 32 - 0)\right] = 0.08$$

‡ For steel $K = F\frac{1.8}{\sqrt[4]{t\,(\text{max.})}} = 66{,}000\ \frac{1.8}{\sqrt[4]{0.0011}} = 652{,}000$

$M_t = 694$ $M_c = 4540$

Hp. $= 2.21$ $D \geqq 1.57$

$M_b = 4505$

The actual consumption of energy on the milling machine driven by motor was 3.4 kw. = 4.57 hp.; therefore the coefficient of useful work of the entire installation was

$$\eta = \frac{2.21}{4.57} = 0.48$$

A comparison of mills with different spiral angles and different rake angles is very interesting. The results of such a comparison are given in the table below. For all observations it is assumed that all mills have the same output or make the same volume of chips per minute, that is, that the product dfh = constant.

	Cutter with straight teeth $\lambda = 10°; \beta = 90°$	Cutter with spiral teeth $\lambda = 10°; \beta = 70°$	Cutter with spiral teeth $\lambda = 12°; \beta = 60°$
M_t	1814	694	646
Hp.	5.77	2.21	2.05
M_c	12700	4540	4610
D	$\geqq 2.21$	$\geqq 1.57$	$\geqq 1.58$
Note:	Work with strong shocks	Quiet work without shocks	Quiet work without shocks

Milling conditions: $D = 1.575$; $z = 9$; $A = 1.575$; $n = 200$; $d = 0.118$; $h = 3.15$; $f = 3.937$; $l = 3.937$; $S = 12{,}000$; $F = 66{,}000$.

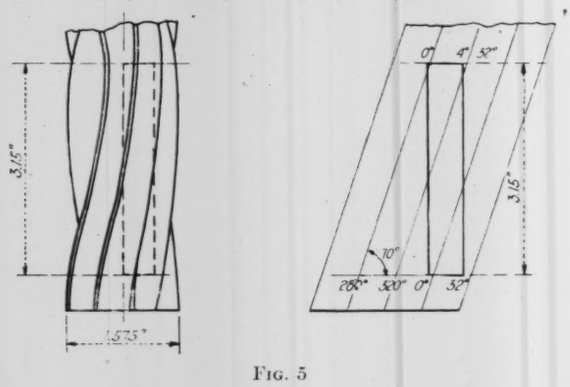

Fig. 5

As shown in the table, a larger rake angle γ is not very useful; neither is a spiral of smaller lead, as with increasing bending moment the efficiency of the cutter will not increase. As far as mills with straight teeth are concerned, milling with such a cutter is accompanied by shocks and the cutter consumes 2.5 times more energy and produces bending moments 2.8 times greater than a cutter with spiral teeth.

Very important is a comparison of milling with cutters producing a constant volume of chips per minute, but having different depths of cutting d. The following table shows that the consumption of energy is nearly the same, also that the torsion moment is nearly the same, but the combined moment M_c for depth $d = 0.315$ in. is 15 per cent greater than for the depth $d = 0.118$ in., and the bending moment is 18 per cent greater.

	$d = 0.118$ $h = 3.15$ $f = 3.937$	$d = 0.315$ $h = 2.362$ $f = 1.9685$
t (max.)	0.0011	0.00082
K	652,000	703,000
M_t	694	789
Hp.	2.21	2.51
M_c	4540	5342
D	$\geqq 1.57$	$\geqq 1.61$

Milling conditions: $A = 1.575$; $D = 1.575$; $z = 9$; $\lambda = 10°$; $\beta = 70°$; $n = 200$; $l = 3.937$; $S = 12{,}000$; $F = 66{,}000$; chips, cu. in. per min., = 1.46.

For side milling the depth of cut d should be small with regard to the outside diameter of the cutter A; it should not exceed the tenth part of outside diameter of the cutter, or $d \leqq A/5$. This fact is explained by theoretical considerations and is corroborated by many practical experiments.

Case IV—End Mills

The general formulas already developed for mills are applicable also to end mills (see Fig. 6). As shown by experiments, the front teeth consume very little energy when they are in good condition, as these teeth only scrape the material. Calculations for these cutters can be made as for plain milling cutters. The axial pressure of the cutter will be compensated for by axial pressure of the spiral teeth, which tends to pull the cutter out of its seat. Therefore the designer, to realize correct cutting conditions, should use for a right-hand cutter a right-hand spiral and for a left-hand cutter a left-hand spiral. This means that he should recognize the condition which has a tendency to pull the cutter out of its seat.

Example IV (Fig. 6). $z = 8$; $A = 1.181$; $D = 0.945$; $\lambda = 10°$; $\beta = 70°$; $n = 150$; $d = 1.181$; $h = 0.827$; $f = 3.15$; $l = 4.921$. Material to be cut, steel; $S = 63{,}400$ lb. Material of cutter, high-speed steel.

$$\alpha = 180°$$

$$\varphi = 45°$$

$$\text{arc } \gamma_h = 0.57$$

$$\gamma_h = 30°$$

$$t\,(\text{max.}) = \frac{3.15}{150.8} \sin 90° \sin 70° = 0.00247$$

$$K = 512{,}000§$$

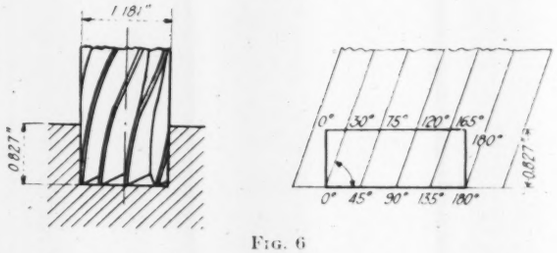

Fig. 6

$$\sum_1^8 B_i = \frac{1}{0.51}(\cos 0° - \cos 30° + \cos 45° - \cos 75° + \cos 90° - \cos 120° + \cos 135° - \cos 165°) = 0.67$$

$$\sum_1^8 C_i = 0$$

$$\sum_1^8 E_i = 2.09$$

$$Q = \frac{Kfh}{nz} = 1069$$

$u = 0.925$

$w = 0.837$

$M_t = 392$

Hp. $= 0.93$

$M_b = 13{,}570$

$M_c = 13{,}570$

$$D^3 = 0.8439 = \frac{32.13{,}570}{3.14\,S}$$

$S = 171{,}000$

After a short period of cutting the cutter breaks in the section of maximum bending moment.

Let us make a comparison of the work of two end mills. The first mill is shown in Fig. 6. The second has the same dimensions, but has only straight teeth. The material to be cut is steel of 53,400 lb. per sq. in. tensile strength. Feed $f = 1.575$ in., width of cut $h = 0.827$ in., $d = 1.181$ in., $l = 4.921$ in., $n = 150$ r.p.m. We can see from the table below that the cutter with straight teeth consumed 3.5 times the energy required by the cutter with spiral teeth. The bending moment of the straight-tooth cutter is smaller.

	$\lambda = 10°; \beta = 90°$	$\lambda = 10°; \beta = 70°$
t (max.)	0.00131	0.00123
K	498,000	512,000
M_t	755	202
Hp.	1.78	0.49
M_c	6640	7200
F_b	79,600	87,000
Note:	Quiet work	Quiet work

Milling conditions: $A = 1.181$; $D = 0.945$; $z = 8$; $\lambda = 10°$; $n = 150$; $d = 1.181$; $h = 0.827$; $f = 1.575$; $l = 4.921$; $F = 53{,}400$.

§ For steel, $K = 63{,}400 \dfrac{1.8}{\sqrt{t\,(\text{max.})}} = 512{,}000$.

CASE V—ARBOR-SUPPORTED CUTTERS

The formulas developed for plain milling cutters can be used for those supported by an arbor. The difference is only in the equation determining the outside diameter of the cutter holder, which is

$$D \geq \sqrt[3]{\frac{32\,M_e}{8\pi S}}$$

Fig. 7 represents a roughing cutter, of outside diameter $A = 5.118$ in. with 5 teeth and with a spiral angle of $\beta = 35$ deg., working

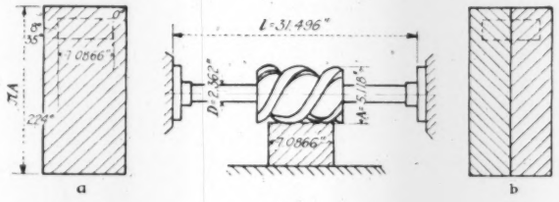

FIG. 7

cast steel having a strength of 80,400 lb. per sq. in. In one case the cutter consists of two halves, one half having a left-hand spiral and the other half having a right-hand spiral to compensate for the axial pressure (Fig. 7*b*). In the other the cutter has a simple spiral. For both cutters, D, Hp., M_t and M_e are the same.

Example V (Fig. 7). $A = 5.118$; $D = 2.362$; $z = 5$; $\lambda = 12°$; $\beta = 35°$; $n = 30$; $h = 7.0866$; $d = 0.472$; $f = 1.181$; $l = 31.496$; $S = 12{,}000$; $F = 80{,}400$ (steel).

$\cos \alpha = 0.81$

$\alpha = 36°$

$\varphi = 72°$

$\text{arc } \gamma_h = 3.9$

$\gamma_h = 224°$

t (max.) $= 0.0026$

$K = 640{,}000$

$\sum_1^\kappa B_i = 0.14$

$\sum_1^\kappa C_i = 0.14$

$\sum_1^\kappa E_i = 0.05$

$u = 0.56$

$w = 0.12$

$Q = 35{,}709$

$M_t = 7165$

Hp. $= 3.42$

$V = 4100$

$M_b = 85{,}240$

$M_e = 85{,}240$

$D \geq 2.126$

The Distillation of Coal

A Discussion of the Principles Involved in the High- and Low-Temperature Processes of Carbonizing Coal, the Difference in the Products Obtained Therefrom, and the Fields for Each Process

By WILLIAM HUTTON BLAUVELT,[1] NEW YORK, N. Y.

THE industries that make up so much of the material side of our civilization are, to a large extent, devoted to improving and increasing the form value of the raw materials furnished us from nature's workshop or the cruder products of our own work. A pound of steel in the form of hairsprings for watches has increased in form value something over 50,000 times above the cost of a pound of the original steel. Among the fuels petroleum is a notable instance of the great increase in value resulting from the application of able and costly research looking to the production of derivatives having higher form values.

Is it not remarkable that coal, one of the most widely used of the raw materials of our industrial life, has been employed almost entirely in its original form? In the production of power from coal nearly all the research and invention has been directed to its more efficient use in the raw state, rather than in endeavors to improve the form value of the coal itself, and by treatment, as in the fractionation of petroleum, for example, to so separate or modify the various constituents of the coal as to obtain the greatest total value. We should surely make an important economic step, if by processing coal in an efficient way the form value could be improved or bodies could be extracted from it of sufficient value to pay for the processing, leaving as residue a better fuel than the original coal.

Coal One of the Materials Largley Used in Its Original Form

In one branch of the coal industry, and practically only one, this result has been secured with notable success. The author refers to the manufacture of coke, which employs many millions of capital and some of the best engineering and administrative talent that can be secured.

This industry has attained a very respectable age. In the early records of the smelting of metals from their ores, we find references to the "burning" of coal in heaps or meilers to make it better suited for use in the crude furnaces of those days. Even the by-product coke oven has its place in those early records. In 1771 Goethe found one Stauf, "philosophus per ignem," near Saarbrucken, endeavoring in his "connected row of furnaces" to "cleanse the coal from sulphur for use in iron works" and "also turn the oil and resin to account, not even losing the soot." But Goethe relates that "all failed together on account of the many ends in view." Since then many failures have paved the way to the firmly established coking industry of today.

During the last twenty years we have heard much of another process for treating coal, generally called "low-temperature distillation," and much time and money has been spent on many processes for treating coal in this way. The author has been asked to discuss the principles involved in the high- and low-temperature carbonization of coal, the difference in the products obtained, and the fields for each process.

First let us try to define the two processes. This is not easy because we have still much to learn regarding the composition of coal and its decomposition under heat.

The High-Temperature Distillation Process

For practical purposes it may be sufficient to define high-temperature distillation in terms of its principal application, viz., the manufacture of coke, since in practice only coking coals are used in high-temperature work.

The coal substances which are responsible for the coking qualities of a coal are not well understood, but we may call them resins. These bodies are found in all bituminous coals, but to produce a satisfactory coke they must be present in suitable quantity to perform their function in the production of coke.

When a suitable coal is charged into an oven it comes into contact with the oven walls which are heated to 1000 deg. cent. or more. The heat begins to pass through the coal toward the center of the oven, and the coal next the hot wall quickly reaches a viscous state due to the melting of the resins. As the heat continues to pour into the coal charge this viscous zone moves toward the center and the first layers solidify into coke. The cellular structure which is typical of coke is formed just as the mass solidifies, and is due to the gases expanding from the heat and forcing their way out of the solidifying mass, leaving behind the spaces they had occupied. The walls of these spaces or cells are hardened as their temperature increases, and the structure of the finished coke is determined by the size and arrangement of these cells and the hardness and thickness of their walls due to the rate and degree of heating and the composition of the coal.

The viscous zone that is produced by the progressive fusion of the coal, at temperatures between 650 and 750 deg. is practically impervious to the flow of the vapors as they are generated, so that often a pound or more of pressure is built up in the center of the charge. As a result all the gas and vapor produced from that portion of the coal between the wall and the viscous zone is forced to travel toward the walls through the hottest part of the coke, and along these hot walls to the gas space above the charge. All these vapors are brought to the maximum temperature in the oven and subjected to a strong secondary reaction, producing a large volume of gas, high in hydrogen, also benzols and the viscous tar, rich in aromatic bodies, all typical high-temperature bodies. A much smaller portion of the vapors, evolved ahead of the fusion zone, escapes through the cooler center of the coal mass without being subjected to much of the secondary reaction.

Low-Temperature Carbonization

Low-temperature carbonization must be conducted in quite a different manner since the destructive characterization of this process is that the hydrocarbons and other volatile constituents of the coal are not subjected, either during or after distillation, to temperatures that will cause any secondary reaction. The limit appears to be about 750 deg. cent., or perhaps somewhat less. The primary tars produced at these temperatures consist mainly of paraffins and tar acids. Some authorities fix the temperature at from 500 to 600 deg., and there is some difference of opinion whether all coals react the same at a given temperature. Of course commercial operations may be carried on at higher temperatures, for one reason or another, but as soon as the distillation products are heated above the critical temperature so that any secondary reaction results, the resulting products are no longer of the purely low-temperature-distillation type. This suggests one of the reasons for the slow growth of low-temperature work to a commercial application: the heat conductivity of coal is low, so it is difficult to design apparatus capable of economical rate of output while maintaining the necessary low temperature gradient to avoid the secondary reactions. This point will be discussed later.

Of course the conditions of low-temperature work preclude the formation of a true coke, since the conditions must be absent which would permit the development of the cell structure which gives the coke its distinguishing characteristics and commercial value. Some have given the name "char" to the solid residue from low-temperature distillation. This "char" may have the shape of the original pieces of coal, or it may appear as balls of irregular size and shape, or in pulverulent form, depending on the process and apparatus employed.

[1] Consulting Engineer.

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DIFFERENCES IN THE GASES AND TARS PRODUCED BY THE TWO PROCESSES

The gas produced by the two processes is quite different both in quantity and quality. The following comparison is perhaps representative:

	High-temperature	Low-temperature
Cu. ft. per net ton of coal	11,000–13,000	4000–5500
B.t.u. per cu. ft.	525–600	675–800
Analyses:	Per cent	
Hydrogen	50.0	27.5
Methane	33.0	48.0
Illuminants	3.0	10.0
Unsaturated hydrocarbons	...	3.1
Carbon monoxide	5.5	7.3
Carbon dioxide	1.5	2.5
Nitrogen and oxygen	7.0	1.6
	100.0	100.0

The tars are also of quite different composition and suggest different, rather than competitive, places in the arts. The representative high-temperature tar is viscous at ordinary temperatures, yields from 50 to 60 per cent of pitch, and its oil is rich in anthracene, naphthalene, and the benzols and other saturated hydrocarbons.

Low-temperature tars, on the other hand, are much more limpid, lower in pitch content, and mainly composed of bodies of the paraffin series, naphthenes, and unsaturates. After the tar acids, mostly cresols, are removed the oils resemble crude petroleum. One observer has found that the hydrocarbon portion of these oils is very similar to Russian petroleum. On distillation and further cracking they yield considerable percentages of light oil suitable for motor fuel, similar to gasoline. The high percentage of tar acids in the oil suggests special value as a wood preservative, disinfectant, or insecticide.

The yields of tar or oil from the two processes are quite different, as might be expected from the conditions under which the operations are carried on. In the high-temperature process the temperatures and the other conditions are favorable to the breaking down of a high percentage of the vapors into gas, resulting in a high yield of gas, as given above, which is at the expense of the tar yield. The tar obtained from ordinary coals amounts to from 10 to 13 gal. per ton.

In low-temperature work, on the other hand, the vapors are not subjected to temperatures which produce a secondary reaction, and the gas that is formed is not diluted with the products of cracked vapors, mainly hydrogen, so the volumes are much less, by perhaps 60 per cent, while the calorific value per unit volume is much greater. The yield of tar, or oil, is correspondingly increased. It is difficult to give in definite figures the yields of oil that may be expected from any representative coal, for the statements of technical writers vary so widely on this point. Any process employing a given temperature and a given coal should yield the same quantity of oil, but oftentimes varying conditions are unconsciously introduced which have a material effect on the results. From a comparison of the gas yields from the two types of distillation process, a yield of over twenty, but not more than thirty, gallons per ton of representative coal seems a justifiable estimate, since the yields of gas and tar are interdependent.

It is hoped that the large amount of development work now in progress will soon perfect apparatus in which distillation conditions can be accurately controlled, so that we may have definite data on this important point.

In high-temperature distillation an important source of revenue is the ammonia, in an amount averaging perhaps 25 lb. per ton of coal, in the form of sulphate of ammonia.

While some ammonia is produced by low-temperature distillation, the quantity is usually not sufficient to justify recovery in a commercial plant.

In the above comparison of the products obtained from the high- and low-temperature processes, the author has considered only one of the two general divisions of low-temperature work. He has discussed results from processes in which the heat required for the distillation is applied externally and reaches the coal through the walls of the containing vessels, as it does in the by-product coke oven, the apparatus usually employed in high-temperature distillation.

PROCESSES IN WHICH HEAT IS DIRECTLY APPLIED TO THE COAL

Several processes have been developed in which the heating medium is applied directly to the coal within the containing vessel either by a current of preheated inert gas or by introducing a controlled supply of air, so that partial combustion takes place.

These processes yield somewhat less coke or char than those first described, a much larger yield of gas, varying perhaps from 60,000 cu. ft. of 150-B.t.u. gas to 25,000 cu. ft. of 240-B.t.u. gas. When air is introduced into the chamber, the oils are generally less in amount and of somewhat different composition. Wellington and Cooper state that "the crude oil is, in fact, more like the heavy-oil distillate from blast-furnace tar." They also say that the yield of ammonia is stated to be high, about the same as from coke ovens. Some of the processes employing internal heating have the advantage of very simple design and operation.

The author has used the externally heated process in his comparison because the differences in results, as compared with high-temperature work, are due only to the different temperatures employed, and are therefore more typical.

FIELDS OPEN TO THE TWO PROCESSES

What are the fields in which the two processes may find practical usefulness as determined by satisfactory earnings on the capital invested in the plant and operation? In the high-temperature process, which is well represented by the by-product coking industry, the field of commercial application has been pretty well demonstrated. All of the products, coke, gas, tar, benzol, and ammonia, are well established in the world's markets.

Coke is recognized as a standard fuel in many metallurgical processes and is rapidly growing in favor for domestic use. Coke plants are delivering all the gas not required for heating the ovens, either for sale to gas companies or for use in metallurgical furnaces, and the supply is as reliable and the quality as good as from any manufacturing plant where gas is the primary product. In fact, many coke plants are run primarily as gas plants. Coke-oven tar furnishes the main supply to the tar industry in this country; coke-oven benzol is a preferred motor fuel and has a ready market in the dye industry and others.

There is a world market for the sulphate of ammonia as a fertilizer.

There is a different situation in the low-temperature field. The usual products are semi-coke or char, either in lumps or in pulverulent form, gas which is considerably higher in calorific value than standard city gas, and tar or oil, the quality and composition of which has been discussed above.

What are the fields for each of the products and how can they reach a profitable market, so as to insure the necessary earnings for the undertaking? There is no established demand, at present, for any of them, either here or abroad, but many new industries have met and overcome a similar situation. Each of the products has undoubted potential value, but perhaps the creation of a demand and adapting each one to this demand is a problem of even more importance than the development of a particular apparatus or process for treating the coal.

Many low-temperature processes have been brought to a degree of perfection, both here and abroad, but it is difficult to choose among them until we have a clear understanding of what market conditions must be met by the several products. In Great Britain there is, just now, greater interest in the coke or char as offering a possible smokeless fuel for their domestic grate fires. In Germany the main interest seems to be in the oils, in the hope of making the country less dependent on foreign petroleum.

In America our variety of coals and our wide extent of territory give a more diversified field and many possibilities. The char may find a market in one locality, when delivered red hot from the distillation plant on to the grates of a boiler plant, an application which promises certain economies. In another place it may create a market for the fines from a lignite mine, where now only the screened lump is salable. Under certain conditions the char from these fines, properly briquetted, should secure a better market than the screened lump.

Low-Temperature Char as a Boiler Fuel

In pulverized form, low-temperature char has already attracted considerable attention as a boiler fuel, and one low-temperature distillation process is based on this use.

The success of a low-temperature char in any field is determined by the extent to which its changed form value increases its sales value in relation to the cost of the processing.

Low-temperature oils have some of the characteristics of petroleum, and others are similar to those of coal tar. Without fractionation or other treatment they are of course marketable as fuel oil. Whether their high content of tar acids, or their considerable yields of motor fuel, when cracked for that purpose, or the value of certain fractions as Diesel-engine fuel, or other characteristics, will secure to these oils a profitable and ready market, can be determined only when a regular and reliable supply is available for experiment and investigation on a commercial scale. Many technicians believe that these low-temperature oils offer the best promise of furnishing a substitute for petroleum when the continued increase of demand over supply has raised the price.

The gas is of course a superior fuel on account of its high calorific value. It is not directly available for use as city gas on account of its being much above usual B.t.u. standards. But it can of course easily be brought down to standard by mixture with a leaner gas, such as blue water gas.

Work Yet to be Done in Low-Temperature Distillation Field

The success of the distillation of coal at high temperatures is firmly established in the coking industry. In low-temperature distillation, however, there is still much to be done. At present there is not a prospect of great profit per unit of product, so the successful apparatus must be simple to operate and of moderate cost. It must permit good control of the heats employed and notwithstanding the low heat gradients, it must have a considerable tonnage output. By no means all the apparatus offered by inventors, in this country or abroad, meet all these specifications.

The author believes there is a place in our industrial life for the low-temperature distillation of coal. Apparatus is being perfected and simplified, and there are many coals which are now of little value which might be processed to yield a profit, if the right market conditions can be secured.

Although the order is often reversed, a successful application of low-temperature distillation can be secured only if a careful and intelligent study is first made of all the conditions of a proposed location. When these are clearly understood a process can be selected which will best meet the situation, and an intelligent conclusion can be reached as to the probable success of the enterprise. In many cases the desire of the inventor or promoter to push his particular apparatus has been the leading influence, with unhappy results.

Low-temperature distillation may seem to progress slowly toward a place in our commercial life, but the history of the development of the by-product coking process may easily be duplicated by the newer process, and perhaps in a much shorter time.

Complete Gasification of Bituminous Coal

A Discussion of the Fundamental Technology and Economics of Gaseous-Fuel Supply, Dealing with the Present Status and Possibilities of the Systems Available for Making Gas for Use in Mechanical and Chemical-Process Industries

By R. S. McBRIDE,[1] WASHINGTON, D. C.

THE greatest advance in industrial fuel utilization in the United States will probably come through complete gasification of bituminous coal. This very sweeping statement requires some qualifying limitations. Moreover, it should not be accepted without thorough proof. The demonstration of its correctness when so qualified is at once the purpose and the justification of this contribution.

This paper is not intended as a discussion of this problem from the standpoint of the city-gas manufacturer or public-utility company's engineer. It is prepared rather in the belief that all chemical engineers and mechanical engineers are equally interested in and should understand the fundamental technology and economics of gaseous-fuel supply. Such engineers are most often the ones responsible for determining the technical policy of the mechanical and chemical process industries. Selection of fuel supply or fuel-processing method is often, therefore, their function. And this problem arises with surprising frequency even in plants where there is no thought of entering into the gas or coke business as such.

"Complete Gasification" Defined

The term "complete gasification" of bituminous coal is commonly understood by engineers to mean the processing of the coal with production of only gas and ash as end products. Usually the term is limited to those processes or combination units in which the raw coal is subjected to a low-temperature coking by the heat generated during the final gasification of the semi-coke. This, however, is a very narrow and limited meaning for the term, and one which will not well serve the present paper.

There have been proposed to accomplish such complete gasification a wide variety of machines and devices, some single-shell generators and others with two or more generating chambers. All of the processes of this character which fall within the narrow definition of the term "complete gasification" have yet to demonstrate under American conditions their commercial usefulness and success. To discuss them would be to consider only a potential division of the fuels industries which has not yet assumed definite form or commercial importance in the United States.

In a broader sense complete gasification should include any process or combination of processes which converts substantially all of the bituminous coal used into fuel gas without manufacturing coke as an *end* product. In this broader sense the gas producer and the water-gas machine when using bituminous coal are complete-gasification devices. Moreover, the combination of any coal-gas or coke-oven unit with a water-gas machine or gas producer using the coke also affords complete gasification. And at least theoretically one might include in this broad group those schemes for steaming coke in the coal-gas retort, for by this means at least part of the coke is gasified.

Proposed "Complete Gasification" Machines

As a supplement to this discussion, any one who wishes to see a brief description of the more important of the proposed machines for complete gasification as defined in the narrower sense, will find this material in recent reports of the committee on carbonization and complete gasification of coal of the American Gas Association. The reports of this committee's work have from year to year included descriptions of the more important types of apparatus which have been used in Europe, and of those types which have been experimentally developed and are still under trial in the United States.

In view of the fact that none of these units has as yet attained commercial form either for city-gas manufacture or for industrial fuel-gas making, it is not necessary to consider them here at length. One should recognize, however, that in Europe, where the relative importance of raw material, labor, and energy supply is quite different from what it is in the United States, several of these processes are in successful operation. It may well be, too, that these will find in the future within the United States a more congenial atmosphere for further development. As yet, however, such development is a matter of conjecture or forecast, not a demonstrated success at any point with which the present author is acquainted.

Why Gaseous Fuel?

For the present discussion the problems of railroad fuel and of fuel for steam-boiler operation in industry and central station are altogether ignored. Obviously gaseous fuel does not lend itself at all well to the problems of locomotive firing. And in the field of steam raising, either for the central station or for the industrial plant, the market is rapidly being preëmpted by powdered coal, and there is no prospect of early replacement of this very efficient fuel by gas. Under these circumstances it can be understood why the problem of gaseous fuel is considered only as an element in industrial heating or household fuel supply.

For many reasons gaseous fuel can be used in the household or for industrial heating to greater advantage than any other solid or liquid fuel. Gas can be burned with a minimum of investment and complication in the user's establishment; it requires the minimum expenditure for labor in firing; and gas can almost invariably be burned with higher thermal efficiency than any other fuel and often can be applied with greater success than even electricity.

There is probably no industrial operation of which it is not at least theoretically true that "If it's done with heat, you can do it better with gas." This slogan of the American Gas Association, of course, does not prove, or even claim, that the heating can *always* be done cheaper with gas. Were this latter possibility proved, there would be a complete and early conversion of *all* other fuel users to gas users. But because gas is so often the best fuel, all things considered, the trend is, in fact, in that direction. And this trend is a rapid one, because in an amazing number of cases the lowest overall cost for industrial heating is obtained with gaseous fuel. All engineers of industry logically, therefore, are wanting to know the prospects for cheap gas.

Three Yardsticks for Measuring Fuel Processes

In comparing several schemes for manufacturing gas no competent engineer would think of considering them only upon the basis of the cost of the gas per thousand cubic feet. Such a yardstick is obviously much too elastic, as the usefulness of gas does not vary as its volume but rather in accordance with the heat which it supplies. When one applies to his estimate of process cost a factor depending upon the heating value of the gas, a very simple yardstick is achieved. This is the cost of a million heat units at the user's plant.

For preliminary study or for the comparison of two different gas supplies this measure, cents per million B.t.u., is substantially correct. In other words, the engineer can with entire safety assume that within the ordinary ranges of fuel-gas character (excluding producer gas from consideration for a moment) a million heat units in gaseous form will do a given amount of work. However, the engineer never should make the mistake of comparing coal with gas, or even oil with gas, on this basis alone. With any other fuel than gas there are variables affecting labor requirement, quality

[1] Consulting Chemical Engineer.

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of products, controllability of heat, etc., which forbid a direct comparison on so simple a basis.

Going one step further in consideration of fuel supplies, managements are often inclined to consider as best that fuel supply which creates the lowest unit cost for the fuel itself per unit of manufactured product made. This "fuel cost per unit of product" is a much better measure than the unit cost of energy, because it does take into account efficiency of burning, labor, and many important factors. However, it is not a perfect measure of the relative merit of fuels because it does not give due credit to several important advantages which can be achieved best with gaseous fuels. For example, such a basis of comparison does not give any credit to one fuel as compared with another on the basis of material spoilage or inferiority in quality of product. It does not take proper account of the higher manufacturing-plant capacity with one fuel than with another; nor does it give proper credit for better working conditions, cleaner plant, and the many incidental advantages with some of the fuels, notably gas.

The only basis of comparison which is complete and absolute is the final balance sheet on annual operation, particularly the profit or loss entries. Such figures inevitably give proper weight to the reduced labor turnover, increased satisfaction to the customer, and the greater output from a given plant, all of which are contributed to if not actually controlled by the choice of fuel.

Bituminous Coal the Logical Gas-Making Material

If the engineer sets about manufacturing gas for industrial and household uses he has a choice of raw materials and of processes. Speaking generally, however, it is necessary to regard bituminous coal as the best of these raw materials, for it is the natural resource still available in almost unlimited quantity and at by far the lowest cost per unit of energy which it supplies. Anthracite, natural gas, and even petroleum are rapidly passing into the luxury class. Thus bituminous coal remains as the logical starting material for gas making.

Recognizing the advantages of gas as an end product and of bituminous coal as the raw material, the engineer must determine to what extent he shall convert the coal into gas and to what extent he can justify, on both financial or technical grounds, a half-way conversion program which affords coke as one of the end products. Naturally in almost every case the comparative process costs will dictate the answer.

City Gas vs. Industrial "Fuel Gas"

In the consideration of this problem the factors which must be studied and their relative importance depend to a very great extent upon whether the gas is to be made in an isolated plant exclusively for industrial use or whether it is to become part of a city-gas supply for public-utility distribution.

In the case of the public-utility gas manufacturer there are many items such as seasonal variation in load, local market for coke, type of gas plant already available, and gas price schedules authorized by the public officials, to determine the extent to which the coke should be sold or be used in further gas making. Those considerations have received a great deal of attention on the part of the committees of the American Gas Association, and are quite generally recognized within that professional field. As a consequence they will be considered only casually in this paper.

The problem of complete gasification of coal for industrial fuel supply has, on the other hand, been little considered in the United States. It is a subject well worthy of attention by the engineering profession, because within the field of industrial fuel for process heating there is no doubt as to the superior performance of gas as compared with any other fuel. And in general the industrial management which finds it necessary to manufacture such gas for its own use does not desire to be forced into the business of making and marketing coke and a wide variety of other coal products. Hence it is quite logical that the industrial management should look to complete gasification as a preferred solution of one of its most important energy-supply problems.

Available Sources of Gas

If a careful and thorough study of any industrial situation indicates that gas is the desirable fuel, the management is at once concerned with the question as to the purchase of this gas or its production within its own plant. For the small works, obviously purchase from a public-utility company is preferred. And in many instances even the largest industrial users of gas find it profitable to buy this fuel supply from a city-gas company, a near-by coke-oven plant, or from some other industrial establishment which has a surplus for sale. Such purchase eliminates from the problems of management the questions of new investment, of directing a new department, in fact, of running an entirely new kind of business.

There are, however, many industrial establishments geographically so located that they cannot purchase gas. Unfortunately it still is true that this geographical factor is in many instances not one of distance from the city-gas supply itself, but simply distance from a city-gas supply marketed under such rate schedules as will make purchase practicable. More and more, however, the city-gas companies are finding it both desirable and feasible to establish such rate schedules as will permit even the largest of industrial fuel users to buy rather than to make the gas which they require. The Peoples Gas Light and Coke Company, of Chicago, is probably the outstanding example in the United States of a concern which markets gas for an untold variety of uses. It has even gone so far as to sell city gas for firing of common brick kilns. And surely if the gas engineers can demonstrate an economy in brick-kiln firing with city gas, it will be an unusual industry that will not fall before the valid arguments of their industrial-gas salesmanship.

But the problem which deserves immediate consideration in this paper is not whether to buy or whether to make. It is what processes are available for gas making for the management, either industrial or public-utility, which must become gas manufacturer. Using bituminous coal as the logical and preferred raw material, and seeking as its objective the complete gasification of this material, the management has then a choice of three general gas-making systems:

1 The gas producer
2 The water-gas machine
3 A combination of coal-carbonizing unit with a producer or a water-gas machine for gasification of the coke.

The present industrial status of these three systems will be briefly considered.

Bituminous Producer Gas

The manufacture of producer gas is well understood among engineers for it is one of the simplest systems of gas making, requiring the fewest mechanical complications, the least investment, and very little operating labor. Were it not for the fact that producer gas, regardless of the solid fuel used, is of such low heating value per cubic foot, this gas would undoubtedly be much more widely used in industry.

The low heating value of producer gas, ranging between 110 and 150 B.t.u. per cu. ft., entirely precludes its use for city-gas supply, either alone or in mixtures with other gases. The cost of distribution of such gas is far too high in proportion to the heat supplied. It is therefore practicable only for use at points in or very near to the producer's plant.

The presence of large quantities of inerts in producer gas not only causes the low heating value per cubic foot, but also prevents efficient utilization unless an elaborate and efficient system of recuperation or regeneration of heat from the products of combustion is employed. Moreover, the maximum temperature attainable in any furnace by burning producer gas is decidedly limited, unless used with a very efficient heat-recovery system, and this is likely to be costly.

All of the objections above cited are of practically the same importance whether coke, anthracite, or bituminous coal is used as a fuel. As a consequence the gas producer for gasification of bituminous coal offers attractive possibilities in only a limited number of cases. With bituminous coal as its solid fuel the producer yields a gas of slightly higher heating value than with coke or anthracite. This advantage is somewhat offset by the fact that it is usually necessary to operate the bituminous-fired producer with provision for recovery of tar, and in some cases also for recovery of ammonia as a by-product.

The gas producer, even when using coke, is really a contributor toward complete gasification of bituminous coal. It is particularly advantageous in such function when using the breeze and fine coke which is otherwise not marketable for household use, for water-gas manufacture, or for general industrial purposes. Using such fine coke the gas producer has found an important function within the coke plant itself for manufacture of the gas to be used in heating the coke ovens. In such service it is in competition with the blue-gas producer.

A very valuable comparison of these two units in such function was presented in 1922 before the American Gas Association by W. R. Morris, of the Seaboard By-Product Coke Company. That comparison demonstrated clearly the greater thermal efficiency, the distinctly greater simplicity and ease of operation, and the lower manufacturing expense in a producer plant as compared with the blue-water-gas plant. But, as he points out there are many circumstances under which the higher heating value of the blue gas, either for use alone or for mixing with oven gas, is a dominating factor, making a decision in favor of blue gas inevitable.

OXYGEN-BLAST GAS

Practically all of the disadvantages of producer gas are traceable to the presence of a large percentage of nitrogen in the finished gas. Hence it has often been proposed that oxygen should be used instead of air for the producer blast. Such a scheme would permit use of bituminous coal with a continuous oxygen and steam blast under easily controllable conditions. In this connection, however, one important mechanical-engineering problem remains without definite solution: that is, whether such producer could be operated without slagging of the ash.

Several chemical-engineering studies to test the necessity for slagging of the ash have been made on a laboratory scale or very small plant scale, but the evidence available is still somewhat conflicting. This matter has been discussed at length in a report by the present author for the Chemical Committee of the American Gas Association, presented at the October, 1926, meeting of the Association. It is unnecessary to review this subject in detail here. It is sufficient to cite here the conclusion that the preponderance of evidence indicates the necessity for a slagging-type producer if oxygen blast is to be used. It seems clear, however, that this will not be a serious complication in case the oxygen-blast producer ever becomes an important commercial possibility. Mechanical engineers have solved many problems which were intrinsically much more difficult than the building of an efficient slagging-type gas producer.

The real problem is, rather, an economic one, that is, the availability of oxygen at a price which would permit its use in gas making.

Estimates indicate that the oxygen-blast producer would require about 30 pounds of coal, about 20 pounds of steam, and about 250 cubic feet of oxygen per 1000 cubic feet of gas made. The resulting oxygen-blast gas would probably range in heating value from 300 to 350 B.t.u. per cu. ft.; in other words, would be comparable in heating value with blue water gas made from bituminous coal.

From very limited experimental evidence some estimates have been made by others that oxygen can be made at a very low cost per thousand cubic feet; but the most favorable estimates which have been confirmable indicate that fuel gas cannot be made profitably with oxygen at the lowest costs that will probably be attained in the United States in the near future, even for large-scale continuous operation with high-capacity load factor. There are, moreover, no oxygen-making plants in existence at the present time of sufficient size even to approach remotely such low estimated cost.

The maximum price which the gas manufacturer can pay for oxygen to make substitution of an oxygen-blast process profitable has been variously estimated at from 17 cents to 50 cents per 1000 cu. ft. of oxygen. An engineering comparison made by the present author indicates that at 20 cents per 1000 cu. ft. for oxygen its use would probably be an attractive commercial proposition; at 50 cents it might under some circumstances be commercially used; but at $1 per 1000 cu. ft., it is likely that oxygen will find very few applications in gas making. And at this point it should be understood that oxygen for some time to come is likely to cost even under most favorable conditions very much more than $1 per 1000 cu. ft.

For the present, therefore, it is safe to conclude that the engineering profession need not look with optimism toward any oxygen-blast process as a means of gas making, either with bituminous coal or otherwise.

BITUMINOUS WATER GAS

Of all systems for complete gasification of bituminous coal the one most thoroughly developed involves the processing of such coal in a water-gas generator. The use of bituminous coal in this way received an initial impetus during the war, especially throughout the mid-western states where anthracite and coke were expensive and difficult to procure. This process has now passed well out of the experimental stage and, in the opinion of gas engineers who have thoroughly studied it, can be undertaken without fear of meeting any serious or unheard-of difficulties.

One of the American Gas Association committees has made a special study from year to year of the use of bituminous coal for water-gas-generator fuel and during the present year, 1926, has prepared a set of instructions for operation of a carbureted water-gas set with 100 per cent bituminous coal. This committee emphasizes the importance of selecting and sizing the coal and of maintaining an operating cycle properly adapted to this fuel. It should be pointed out, however, that there are many mines from which suitable coal can be had, if properly sized, and that wide variations in period of blast, run, and purge are possible with good operating results, just as when coke or anthracite is used.

Some special systems of operation are advantageous, such as "back run," "blow run," "the Chrisman cycle," and like operating procedures, each of which has its ardent advocates. There is also considerable evidence that the use of the "pier" process is particularly advantageous when completely gasifying bituminous coal. This "pier" process involves only a simple variation in the water-gas machine from that commonly employed. As indicated by the name, a pier of refractory masonry is built in the center of the generator supported on the grate bars. By this means the distance from wall to wall within a big machine is effectively reduced so that uniform operating conditions can be maintained throughout the entire fire area. This advantage, it is claimed, accounts for the improved operating results which are frequently experienced when the "pier" process is employed. Certainly this process has done much to stimulate interest in the use of bituminous coal, and thus has had a large psychological as well as considerable engineering advantage.

OPERATING POSSIBILITIES

When using bituminous coal in the water-gas machine the blue gas made may be of slightly higher heating value, up to 330 or 340 B.t.u. per cu. ft., than with coke as fuel. But the experience of some engineers indicates that a cycle involving a "blow run" is necessary. And when the blow run is used the hydrocarbons and other products of partial distillation of the raw coal in the top of the generator are diluted with some additional inert products of gasification. The resulting mixture is then of about the same heating value, 300 B.t.u. per cu. ft., as blue gas made from coke or anthracite.

Engineers who are considering the use of bituminous coal in a water-gas machine should make a careful study of the 1926 committee report above referred to. In it they will find set forth the more important precautions which should be observed in adopting such fuel. With proper precautions bituminous coal can be safely used, even some of the mid-continent bituminous coals which earlier fell into disrepute among gas makers because they were very friable, had high percentages of inert volatile matter, and otherwise misbehaved in the generator.

Moreover, by observing suitable precautions and adopting proper operating methods it now appears that the gas-making capacity of a generator need not be materially reduced by substituting bituminous coal for other solid fuel containing no volatile matter, and it seems that clinker troubles and practical operating difficulties are not increased by such a change. As a generalization, therefore, it is safe to conclude that the use of bituminous coal in a water-gas generator either of the conventional or of a special type really affords the finest prospect for complete gasification at present available to the American engineer.

Blue Gas vs. Carbureted Gas

If the engineer has reached such conclusion, that use of bituminous coal in the water-gas generator is desirable for his local conditions, he is still confronted with the problem as to whether the blue gas should be used as such, at 300 B.t.u. per cu. ft., or whether it is necessary to enrich it to some higher heating value.

In general, for city distribution it is not practicable to supply a gas of 300 B.t.u. per cu. ft. For the present, at least, such gas could not be satisfactorily and efficiently burned in existing household and some industrial appliances without extensive and expensive changes. Moreover, even assuming the same efficiency and convenience in utilization, the distribution cost for such leaner gas usually precludes its economic supply throughout a city system.

Fortunately the industrial-plant engineer does not need to consider this item of distributing cost, nor is there usually any difficulty in burning blue gas with high industrial-plant efficiency. As a matter of fact, it is probable that no other gaseous fuels are as efficiently useful in properly designed apparatus as carbon monoxide and hydrogen. These make up practically all of the useful part of blue water gas. Hence for industrial purposes there is no necessity for carbureting this gas with oil or for mixing it with other rich gases as is commonly necessary for public-utility systems. It is worth while, however, for all engineers to understand the special problem of this type which confronts the public-utility engineer in his choice of enriching gas between coal gas and the oil gas made by carbureting water gas.

Coal Gas vs. Gas Oil

When oil suitable for gas making is cheap enough so that the delivered cost to the customer is lower per million heat units with carbureted water gas than with a mixture of coal gas and blue water gas, the engineer may retain a semblance of complete gasification of the bituminous coal. Under such circumstances he does not need to turn to coal gas, with its consequent manufacture of coke, as the enriching medium. But at the present time gas oil is available in constantly decreasing quantities and is being sold at constantly increasing prices. The change from oil to coal as enricher is therefore in progress.

The petroleum refiner appears to have reached the conclusion that any petroleum fraction which is suitable for carbureting water gas is also suitable for gasoline manufacture in his own plant. Such light fuel oil, whatever its trade name, is worth to the refiner about 60 per cent as much per gallon as he can get for gasoline. Thus when gasoline is worth 15 cents at the refinery, gas oil should be worth 9 cents per gallon to the refiner. And when gasoline attains a refinery price of 20 cents, not an unreasonable expectation for the near future, such gas oil will presumably be worth 12 cents a gallon. And there is no gas manufacturer in the United States who can afford to pay 12 cents a gallon for oil with which to carburet water gas when bituminous coal is available at anything like present-day prices.

Under these circumstances it seems evident that we shall see a very large further swing away from carbureted water gas toward coal gas as the primary step in gas making. As that swing takes place there will undoubtedly be increasing quantities of coke used in blue-gas machines. By this means the output of oven gas will be supplemented in varying amounts as the seasonal requirements make necessary.

Complete gasification of all the coke would, however, produce a mixture of oven gas and blue water gas rather too lean to permit economic city supply. Such a mixture would, however, be entirely suitable for industrial use, and in many cases may be so employed. It is necessary, however, that any combination of coal-gas base load with blue-water-gas admixture be limited as to variation in the proportions of the two constituents. This is essential so that reasonably uniform specific gravity, reasonably uniform heating value, and satisfactorily uniform appliance operation shall be maintained at the gas customers' premises throughout the year. This is particularly important in the case of household gas appliances, because it is not feasible to change the adjustment or the method of operation of such burners every time there is a change in the performance of the gas mixture supplied. Industrial users' appliances, not only because they are fewer in number but also because they are under closer supervision by skilled men, can often be adjusted more easily to meet such seasonal changes without serious difficulty or material expense.

At this point it should be emphasized that the ultimate criterion of comparison between gases must be the cost per million heat units delivered to the users' premises. For industrial gas supply the factory manager may consider the cost per million heat units in his gasholder. But for a public-utility system this "net holder cost" is not the final or determining factor. The neglect of very important considerations, affecting distributing cost and general or commercial expenses, may come about if conclusions are drawn solely on the basis of the net holder cost per million B.t.u. This fact is well recognized by many engineers but its neglect has occasionally resulted in false conclusions for public utilities. In comparing two gases of different heating value for use at points other than the manufacturing plant, a similar precaution should be observed. The *delivered* cost per million B.t.u. is in all cases the more significant basis for comparison.

Steaming of Coal-Gas Units

To give increased output per ton of coal processed and to accomplish other important improvements in plant operation, many attempts have been made to steam the coke within a retort or oven. These practices are even more extensively employed abroad than in the United States, and seem to be again growing in favor in this country. Among the arguments advanced are the increase in gas yield with a given investment and a given amount of labor; increase in yield of certain by-products, notably ammonia; and, in some types of apparatus, an improved heat distribution throughout the carbonizing chamber.

In no case, however, has it proved at all practical to extend the steaming of retorts to the point that even approaches complete gasification. Such a scheme is far less economical than the combination of retort with water-gas set. And, of course, the mixture of coal gas with blue gas from such steaming would be of the same low heating value as that from other complete gasification schemes. Thus complete gasification of bituminous coal in the retort or oven is seen to be impractical.

Manufacturer or Public Utility?

Rarely is an industrial management willing to undertake all the responsibilities and complications of running a coke oven and a water-gas plant in combination simply to obtain its own fuel-gas supply. Such management can, however, often make possible the most economic combination of coke-oven gas and water gas by becoming the coke customer of the nearby coke-oven owner.

Speaking broadly the country needs such a combination of blue water gas or lightly carbureted water gas manufacture with coke ovens to supply the base load for city gas and the needed by-products, such as tar, ammonium sulphate, light oils, and coke. In a recent article J. A. Perry, of the United Gas Improvement Company, has demonstrated the limitations and advantages of such a combination for city-gas supply. It is evident from Mr. Perry's paper and from the great mass of evidence available elsewhere that complete gasification will be accomplished only when much of the coke made in the gas retort or coke oven is afterward processed in a separate plant.

Such subsequent gasification can be just as efficiently carried out by industry as by the gas company, using either the gas producer or the blue-water-gas machine. Where a city-gas supply is not available under rate schedules that lend themselves properly to the industrial use of this gas, it is likely that the manufacturing plant will make its fuel-gas supply from coke in some such manner. And fortunately it appears that this overall economy, so important nationally, will be achieved with accompanying conservation of new investment, conservation of operating labor, and—most important of all—through efficient coal utilization, which is the truest conservation.

Under these circumstances the fact that complete gasification of coal in the narrow use of that term has not yet been realized need not discourage any one. As a matter of fact, complete gasification in its broader and truer sense is today being realized. And it is today within easy reach of any industrial management which has a serious problem of industrial energy supply.

The Low-Temperature Carbonization of Coal

A Statement of the Fundamental Principles Involved and a Brief Discussion of the Present Status of Representative Types of Processes

By A. C. FIELDNER,[1] PITTSBURGH, PA.

THE subject of processing coal by carbonization and gasification is logically divided into three branches, namely, (1) high-temperature carbonization, as in coke ovens and gas retorts, operating at temperatures of 1800 to 2200 deg. fahr. (980 to 1200 deg. cent.); (2) complete gasification, in which coal is converted to gas, ash, and end products other than coke or char, either in a one- or two-stage process; and (3) low-temperature carbonization, in which the distillation temperatures are usually kept below 900 to 1300 deg. fahr. (480 to 700 deg. cent.) to avoid as far as possible the decomposition of primary tar and thus obtain a maximum yield of liquid products. At low temperatures the tar yield is from two to three times that of the high-temperature process. High-temperature carbonization and complete-gasification processes are in common industrial use in the gas and coking industry; likewise complete gasification is a well-recognized industrial process for the manufacture of producer gas and water gas. But low-temperature carbonization has not as yet proved a commercial success, although several large-scale experimental plants have made considerable progress toward solving the many technical difficulties involved in the problem. In the restricted space of a short paper like the present one the author is compelled to limit himself to fundamental principles and a short discussion of the present status of representative types of processes. For further information regarding these processes those interested are referred to the extensive literature on this subject that has appeared in the last few years.[2]

Objectives of Low-Temperature Carbonization

The principal objectives of low-temperature carbonization are:

1 To produce a smokeless, easily ignitible solid fuel for domestic purposes.

2 To obtain a larger yield of liquid fuels than can be obtained from high-temperature processes.

3 The recovery of by-product oils and gas by precarbonizing power-plant fuel, with resulting increased returns from the by-products and beneficiation of the solid fuel, for either pulverized or stoker firing.

4 To provide a substitute for low-volatile semi-bituminous coal, for blending with high-volatile swelling coals in order to make a suitably dense metallurgical coke.

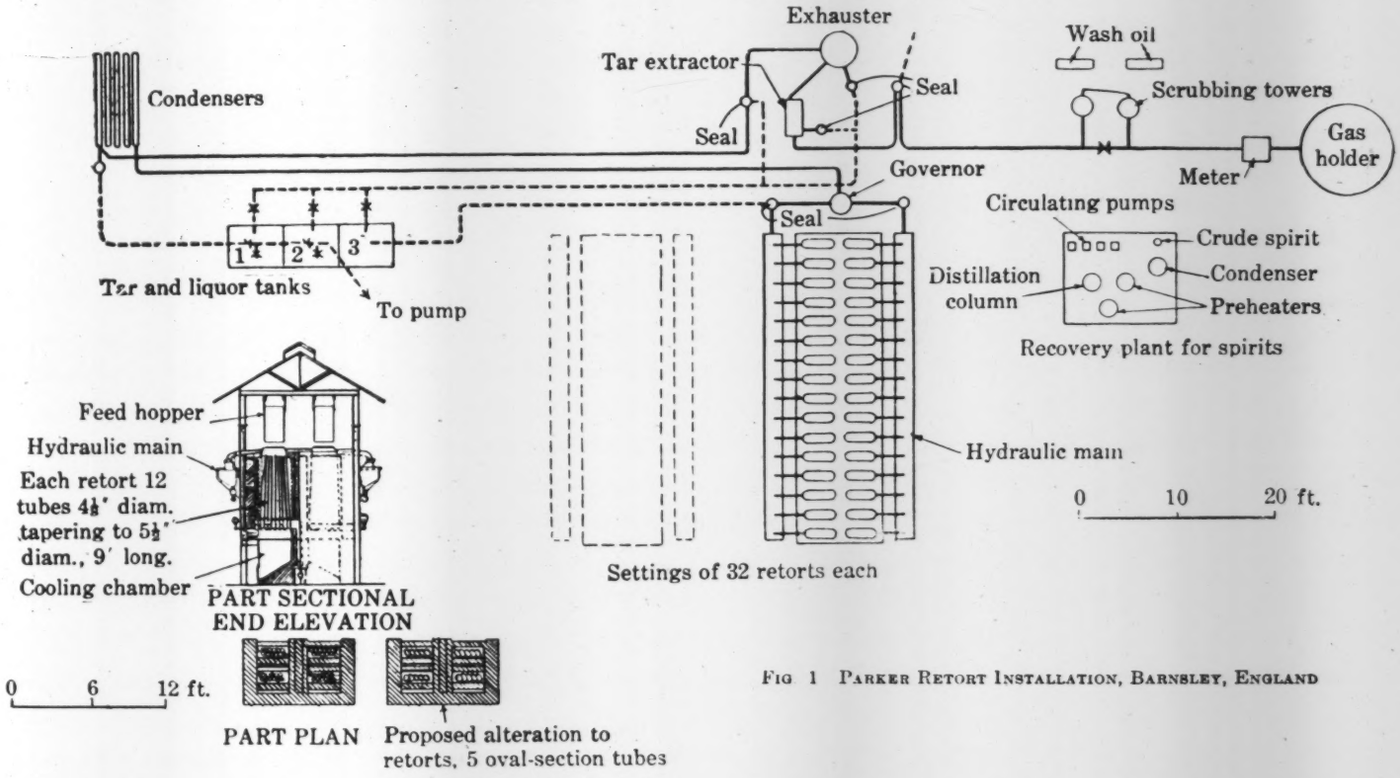

FIG 1 PARKER RETORT INSTALLATION, BARNSLEY, ENGLAND

Of these four objectives, the one common to all low-temperature processes is the increased oil or tar yield. Liquid fuel, especially gasoline, seems essential for the continuation of our present highly developed system of automotive transportation. Petroleum resources are much more limited than coal and may become inadequate to meet the growing demands within the present generation, hence the interest in methods for obtaining this convenient form of fuel from our very much larger supply of solid fuel. European countries which have no internal petroleum resources have a particularly keen interest in this problem, because of the need of a home source of petroleum substitutes in case of being shut off from foreign supplies during an extended war.

Methods of Heating

The fundamental difficulty in carbonizing coal at low temperatures is in transferring heat to the coal in a reasonably short time when using a relatively low-temperature gradient. Coal is a poor conductor of heat. It takes much longer to transfer the necessary amount of heat through a given volume of coal when the retort walls are at a temperature of 1100 deg. fahr. (600 deg. cent.) than when they are at 2200 deg. fahr. (1200 deg. cent.) as in the usual

[1] Chief Chemist, U. S. Bureau of Mines, and Superintendent, Pittsburgh Experiment Station, Pittsburgh, Pa.

[2] The Low-Temperature Carbonization of Coal, by A. C. Fieldner, Technical Paper No. 396, U. S. Bureau of Mines, 1926.

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high-temperature process. Experience has shown that four or five inches is the maximum thickness that can be carbonized at low temperatures in a single-stage static process in a reasonable length of time; hence it becomes necessary to use a multiplicity of small-diameter retorts or to accelerate the rate of carbonization, either by spreading the crushed coal in a thin layer on a heated surface or by agitating the coal, bringing fresh portions continually in contact with the heated walls or by passing large volumes of hot producer gas, products of combustion, or superheated steam through the mass of broken coal.

Differentiating on the basis of method of heating, the various processes fall into two classes, namely, (1) externally heated retorts, in which the coal to be carbonized is supplied with heat through the walls of the retort and in which the products of distillation are not diluted with flue gases; and (2) internally heated retorts, in which the coal to be carbonized is heated by direct contact with hot gases or superheated steam which is passed through the retort in intimate contact with the charge.

Carbonization processes may be intermittent, in which the coal is charged into an empty retort and remains there until distillation is completed, when the entire mass of coke or residue is discharged at one time; or they may be continuous, in which charging and discharging is continuous or in small increments.

Present high-temperature by-product coking practice is intermittent, as intermittent processes generally produce firm and lumpy coke. Continuous vertical retorts are coming into considerable use in the gas-making industry as continuous processes favor larger outputs and cheaper operation; the coke, however, has somewhat inferior physical properties to that produced by intermittently charged retorts.

With respect to the style of construction, retorts may be classified as follows: (1) Oven types, usually of rectangular shape, as the standard by-product oven; (2) the vertical shaft type, as in the vertical gas retorts or the Scottish oil-shale retort; and (3) rotating cylinder types, vertical, horizontal, or inclined, similar to revolving driers or cement kilns; the cylinder type may also be stationary, with a revolving internal stirrer.

Classification of Low-Temperature Carbonization Systems

A convenient classification for the many proposed processes is as follows:

A—Externally heated retorts; coal in narrow retorts or thin layers, not stirred:
- 1 Vertical layers of coal in narrow retorts
- 2 Horizontal thin layers of coal.

B—Externally heated retorts; coal stirred in contact with heated surfaces:
- 1 Vertical retorts
- 2 Horizontal retorts
  - *a* Stationary retorts with internal stirrers
  - *b* Rotating cylinders.
- 3 Retorts with coal stirred on a flat heated surface

C—Internally heated retorts; coal in direct contact with hot gases or liquids:
- 1 Hot gases generated by air or air and steam blown into the retort
  - *a* Coal charged in lumps or briquets
  - *b* Coal charged in pulverized form
  - *c* Complete gasification.
- 2 Hot gases or vapors generated outside the retort:
  - *a* Combustion products
  - *b* Producer gas
  - *c* Water gas
  - *d* Coal gas
  - *e* Superheated steam
  - *f* Combinations of above.
- 3 Melted lead in contact with coal.

D—Two-stage carbonization, to control the sticking properties of coal.

It is evident from this classification that almost every possible method of heating has been tried. In the present brief review of the present status of low-temperature carbonization the author will confine himself to a few of the better-known processes of some of the various types which illustrate the different methods of attack and from which certain principles have been established.

Externally Heated Retorts—Intermittent Process—Coal Not Stirred

Parker Process. The manufacture of illuminating gas as invented by Murdock in 1797 and conducted in England up to 1835 was a strictly low-temperature process. The coal was heated in cast-iron retorts at 1000 to 1200 deg. fahr. The advantages of higher temperatures in decreasing the time of carbonization and increasing the yield of gas per ton of coal began to be recognized. Cast-iron retorts were gradually replaced by retorts made of molded fireclay, or built up of segmental bricks and tiles. Likewise in the coke industry, better quality of metallurgical coke and increased oven capacity have favored increasing the temperature as fast as developments in refractories permitted it. Until recent years tar and other liquid products were of little value, and all efforts were directed to complete decomposition of the coal into coke and fixed gas. T. Parker in England was perhaps the first to recognize the desirability of reverting to lower temperatures to obtain a smokeless solid fuel which retained about 8 to 12 per cent volatile matter to make it more easily ignitible and thus more convenient for domestic fuel in open-grate fires. His first patent was taken out in 1890 and his low-temperature process was developed into a large-scale plant about 1908. This plant consisted of cast-iron vertical retorts, about 10 feet long, tapering in diameter from about four inches at the top to about six inches at the bottom. Twelve tubes were cast together in a nest, and heated externally so that the material reached a temperature of about 840 to 930 deg. fahr. The low-temperature coke, known as "Coalite," was found to be admirably suitable for a domestic fuel.[3] However, the retorts failed to withstand the temperatures without distortion and the plant had to be abandoned. Later, firebrick retorts of rectangular cross-section were tried also without success, and finally in 1924 Low Temperature Carbonization Limited built another experimental plant near Barnsley, England, in which they again employed the Parker 12-tube cast-iron retort (Fig. 1) in the hope that the difficulties in discharging the coke due to distortion of the retorts could be avoided by using a special cast iron designed not to grow at temperatures below 1200 deg. fahr. Thirty-two of these 12-tube retorts constitute a battery which has a capacity of 50 tons of coal per 24 hours. The author saw this plant in operation in the summer of 1924 shortly after its completion and after the official tests reported by the Fuel Research Station.[4] The yields obtained in this test are given in Table 1.

TABLE 1 RESULTS OF TESTS BY FUEL RESEARCH STATION OF BARNSLEY PLANT

Coke (6½ per cent volatile matter), per cent	70
Gas (700 B.t.u. per cu. ft.), cu. ft.	5620
Crude tar (dry), U. S. gal.	20
Ammonium sulphate, lb.	12.2
Crude light oil from gas, gal.	1.9
Refined motor spirit to 170 deg. cent., gal.	1.5
Retort temperatures, deg. cent.	600 to 800
Volatile matter in coal, per cent	35

It will be observed that the temperatures were from 100 to 300 deg. cent. above that of the usual low-temperature processes. This accounts for the volatile matter in the coke being 6 per cent instead of the normal figure of 10 to 15 per cent. The tar also suffered some cracking, which resulted in a relatively high yield of light oil and gas, as judged by strictly low-temperature standards.

The Barnsley process was devised primarily to make a smokeless solid fuel for domestic purposes, and it accomplishes this purpose. The cylinders of coke as discharged from the retort fracture into triangular sections about three inches long. The coke is hard and compact and less than 5 per cent passes a ½-in. screen. It ignites readily and gives a cheerful glowing fire. In other words, it is an excellent smokeless fuel.

This process has been referred to in some detail because it represents conditions that will produce suitable smokeless lump fuel,

[3] Low Temperature Carbonization, by C. H. Lander and R. F. McKay. Ernest Benn, Ltd., London, 1924, p. 196.

[4] Report of Tests by the Director of Fuel Research on Parker Low-Temperature Carbonization Plant Installed at Barugh, Barnsley, at the Works of Low Temperature Carbonization Ltd. Dept. of Scientific & Industrial Research. H. M. Stationery Office, London, 1924.

a high-B.t.u. gas, an equal quantity of light oil, and double the quantity of tar as compared to the high-temperature process. The disadvantages are (1) high cost of operation in charging and discharging so many small test-tube-like retorts, and (2) doubtful life of the cast iron at the temperatures employed. Any warping of the metal will increase the difficulty of discharging the coke. Granting technical success, it is questionable whether this process can be carried on economically in competition with present high-temperature gas or coke-oven practice. Recent reports are that operations at the experimental plant have been discontinued for some time and that the company is now in the hands of the receiver.

EXTERNALLY HEATED RETORTS—INTERMITTENT TWO-STAGE PROCESS—COAL NOT STIRRED IN FINAL STAGE

Parr Process. At about the same time that Parker was developing his Coalite process in England, Prof. S. W. Parr at the University of Illinois began to study the production of a smokeless fuel from Illinois coal. These investigations, begun in 1902, were first published in 1906 in the Year Book of the Illinois State Geological Survey for 1906 under the title, The Anthracizing of Bituminous Coal.[5] Other publications followed showing that an

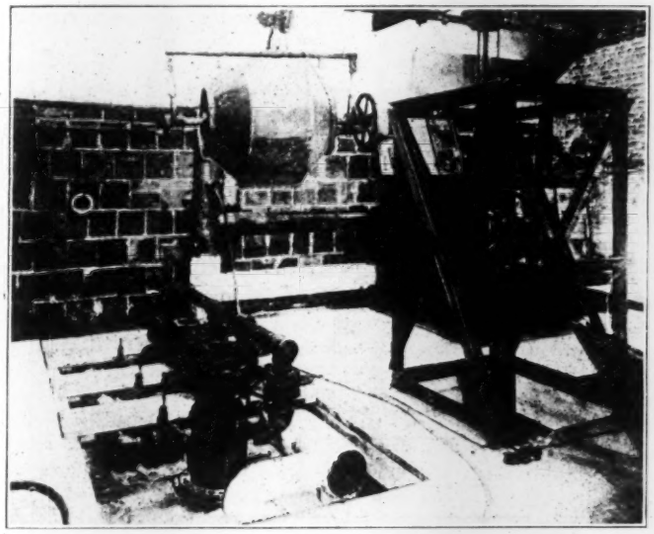

FIG. 2 PARR DRUM PREHEATER (EXPERIMENTAL)

excellent domestic smokeless fuel could be made from the carbonization of Illinois coal at low temperatures. Parr employed a vertical cylindrical iron retort externally heated and intermittently charged (the same principle as Parker), but in the development of his process he has overcome Parker's limitation of small retort diameter by utilizing the exothermic heat of carbonization of coal. This is done by heating the coal in two stages, which greatly increases the capacity of the installation by permitting the use of large-diameter retorts without increasing the time of carbonization. In Professor Parr's own words, quoted from his Chandler Memorial Lecture[6] delivered at Columbia University, April 23, 1926, his process is as follows:

> First, the preheating of the coal out of contact with the air, nearly but not into the pasty stage. This of course must be accomplished evenly in a closed chamber, externally heated and rotary in type to insure an equal dissemination of the heat throughout the mass. In Fig. 2, at the right is housed a rotary drum, heated by waste gases from the flues with accessory gas burners for supplemental heat. By this means the temperature is under ready control and may be arrested at any stage without detriment, for the reason that the gases resulting from the heating are automatically discharged from the system and the preliminary reactions are at substantially a standstill unless the heat is carried into the plastic stage, say, 350 deg. (662 deg. fahr.). No hydrocarbon decomposition occurs until the pasty stage is reached. After this preliminary treatment, the material still granular and in part plastic is poured into a vertical retort already heated to the desired stage say, 750 deg. (1382 deg. fahr.). Here the external heat plus the reactional heat quickly advances the temperature throughout the mass, well into the plastic condition, say, 400 deg. The metal retorts are here shown without the enclosing brickwork and flues (Fig. 3). From this temperature the process of decomposition may be carried to completion. In the work as we have developed it, having in view the amount of gas and the quality or type of tar desired, the temperature is advanced to about 700 deg. (1292 deg. fahr.) at the center of the retort and this is accomplished in from two and a half to four hours of time.
>
> The retorts used are 14 in. in cross-section at the bottom and 12 in. at the top. Moreover, this quick thermal penetration is accomplished with a heat head at the walls, that is, in the flues, of only 750 to 800 deg. (1382 to 1472 deg. fahr.). If this heat head only were used and the retort charged with fresh coal at normal temperatures, the coke structure would never form, as may be readily understood, for the reason that it would require 24 hours or more to attain a temperature even approaching the pasty stage, say, 350 deg. (662 deg. fahr.), and under such conditions, by reason of the deleterious reactions already described, the softening property would be entirely lost. The mechanical appliances for meeting the conditions are thus seen to be comparatively simple.
>
> Time will not permit of more than mere reference to the results. The main objective throughout the many years of experimentation has been to produce a fuel especially adapted to domestic use. The product is entirely smokeless in combustion, kindles readily, retains its fire indefinitely, responds quickly to draft regulations, and has a strength and density which meets in excellent manner the commercial requirements of handling, shipping and storage (Fig. 4). There is no loss from the production of fines, and the amount of breeze produced is negligible. A peculiar property of the

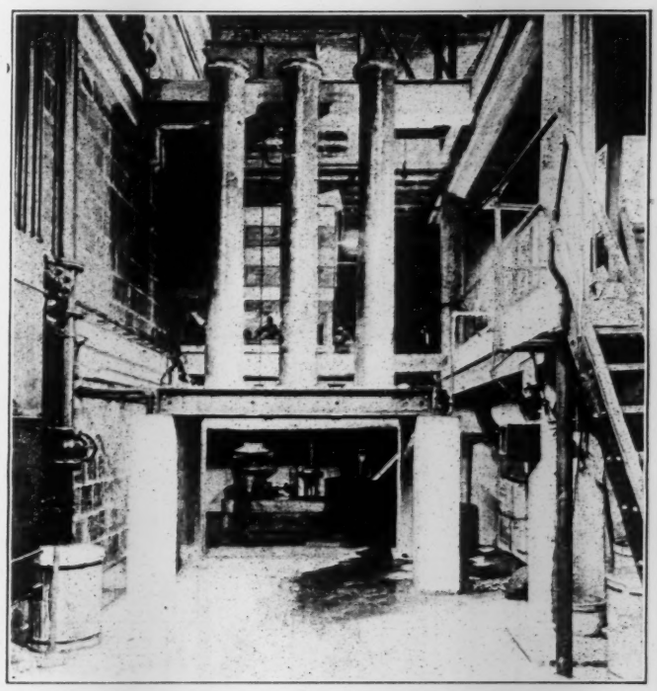

FIG. 3 PARR RETORTS UNDER CONSTRUCTION

FIG. 4 PARR SEMI-COKE (ILLINOIS COAL)

[5] S. W. Parr and C. K. Francis, The Modification of Illinois Coal by Low-Temperature Distillation, University of Illinois Engineering Experiment Station, Bull. No. 24, 1908, p. 14.

[6] *Industrial & Engineering Chemistry*, June, 1926, pp. 640–648.

product in the matter of reactivity toward oxygen is an exceedingly interesting feature. The coke formed at the temperatures indicated, namely, 700 to 750 deg. (1292 to 1382 deg. fahr.), has certain combustion characteristics especially in the matter of retention of fire and quick response to the opening and closing of dampers which is in marked contrast to that of raw coal. Wide fluctuations in temperature are thus avoided and under conditions which preclude the possibility of producing smoke.

I think we have made between 75 and 100 runs and something over 20

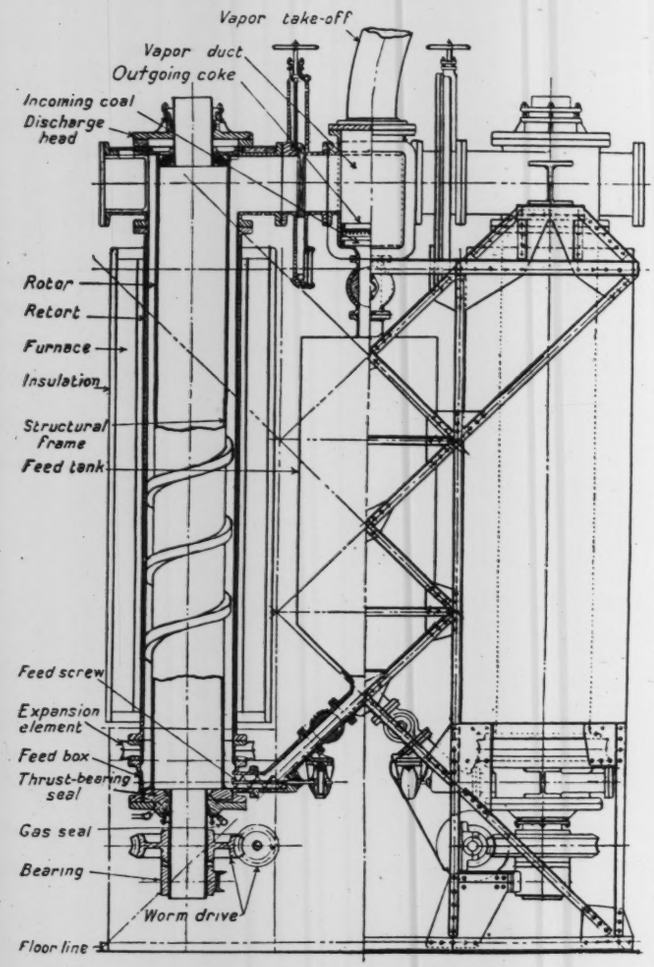

FIG. 5 GREENE-LAUCKS RETORT

tons of coal have been put through the process. This has been quite sufficient to make some rather thorough tests in house-heating appliances from hot-air and hot-water heaters to the open grate. All the reports are exceedingly enthusiastic as to the behavior of the material in actual action.

The University has entered into a contract with the Burgess Laboratories of Madison, Wisconsin, and Chicago, for operating the process on a commercial scale. Preliminary work on their part, however, of an experimental nature looking to that end will be continued under the contract with the University until the first of October, by which time, if the present favorable results continue, the newly formed corporation will be ready to erect a semi-commercial unit, capable, perhaps, of putting out approximately 100 tons per day.

The time of carbonization in the 14-in. retort in the Parr process at a temperature of 700 deg. cent. (1292 deg. fahr.) is 5 to 6 hours in comparison with 4 hours in the Parker 5-in. retorts at 650 to 700 deg. cent. (1202 to 1292 deg. fahr.). This is a very decided commercial advantage in low capital, operating, and maintenance costs. Furthermore the Parr process produces a high-grade smokeless lump fuel from low-rank poorly coking Illinois coals. The tar yields vary from 14 to 16 gal. per ton of as-received coal. These are to be described in a paper by S. R. Church in the December, 1926, number of *Industrial and Engineering Chemistry*.

EXTERNALLY HEATED RETORTS—CONTINUOUS PROCESS—COAL STIRRED GENTLY

The Greene-Laucks Process. Probably the most attractive field for smokeless-fuel production is in the Illinois district. Most of this coal is high in moisture and is not suitable for metallurgical coke. The mines have a large surplus of fines that is difficult to sell at any price. The Old Ben Coal Corporation, recognizing the possibility of beneficiating this low-grade coal, has developed the Greene-Laucks process. In this process the coal is propelled upward by a screw conveyor in a vertical retort in which heat is applied on the outside and within the hollow conveyor shaft. The temperature of the heating flues is graded from higher at the top to lower at the bottom. Fig. 5 shows the 36-in.-diameter experimental retort which has a capacity of 24 tons per day. The action of the slowly revolving screw exerts enough pressure on the plastic coal to agglomerate coal screenings into marketable sizes of lump coke, some of which is very dense, in fact, heavier than water. The maximum temperature is about 930 deg. fahr. (500 deg. cent.), consequently there is said to be little if any deterioration of the

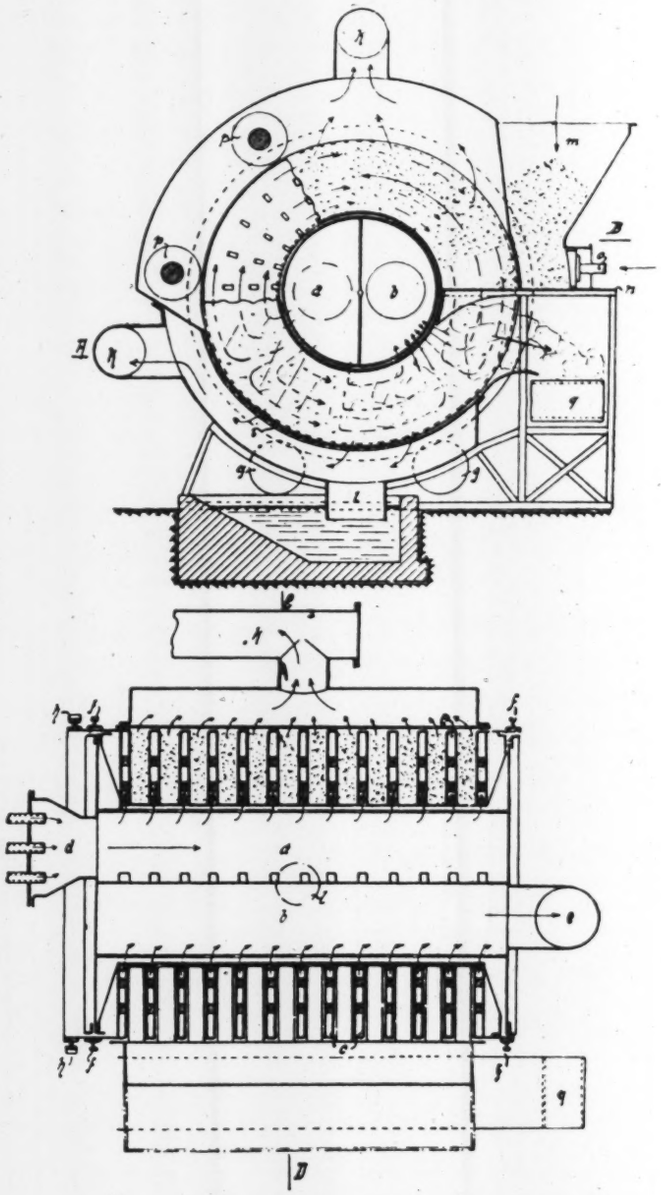

FIG. 6 DOBBELSTEIN RETORT

metal parts. The Old Ben Coal Corporation is now erecting a larger experimental retort on the same principle, but 9 ft. in diameter, at their mines in Franklin County, Illinois. Further development will be watched with much interest because this process gives promise of solving the problem of making a dense lump smokeless fuel from cheap coal by continuous carbonization. Most continuous processes in which coal is mechanically stirred, produce a soft, friable semi-coke unsuitable for domestic fuel without briquetting.

EXTERNALLY HEATED RETORTS—CONTINUOUS PROCESS—COAL NOT STIRRED

The Dobbelstein Process. The Dobbelstein retort developed recently in Germany is also of interest because it is said[7] to produce practically all lump coke of high density and small pores, from coking coals in a continuous operation without disturbing the charge during carbonization. Fig. 6 shows the experimental retort installed at the Bottrop Collieries of the Rheinstahl Arenstein Company near Essen. The retort consists essentially of an inner stationary horizontal steel cylinder divided longitudinally into two compartments, *a* and *b*, by a vertical steel plate. This cylinder is enveloped by another closely fitting revolving cylinder which carries at short distances from each other (4-in. spaces) a series of hollow cast-iron disks (*c*). The revolving-cell system is surrounded by a stationary steel-plate housing, with coal hopper *m* and pistons *o* on one side to charge the coal into the spaces between the disks, gas offtake *K* at the top, and discharging plows near the bottom. The heating gases pass from one compartment of the inner cylinder through the hollow cells and back into the other compartment. The cell system revolves once in 3 to 5 hours in which time the coal is completely coked. The heating gases enter the cells at 550 deg. cent. (1022 deg. fahr.) and leave at 350 deg. cent. (662 deg. fahr.). The coke contains about 10 per cent of volatile matter. The experimental oven, 5 ft. in diameter and 5 ft. long, has a daily capacity of 10 to 15 tons. Two longer retorts of the same design are being installed at certain coal mines in Germany. The performance of these ovens over a period of several years will have to be known before any conclusions as to its commercial success can be drawn. Other designs of retorts in which mechanical pressure is applied to the coal while in a plastic condition, such as the Raffloer, Summers, etc., are described by David Brownlie.[8]

EXTERNALLY HEATED HORIZONTAL OR INCLINED ROTARY RETORTS

From a mechanical point of view the simple rotating cylinder similar to a cement kiln or rotary drier would seem to be the simplest method of carbonizing coal at low temperatures, the advantages being mechanical simplicity, effective heat transfer due to rolling over of the charge with successive contact of all parts of the charge with the heated wall of the retort, and continuous flow through the retort. Among the well-known processes using this type of retort are the Thyssen, Fellner-Ziegler, and Kohlenscheidung Gesellschaft in Germany; the Fusion Corporation in England; and the "Carbocite" or Wisner in the United States. Fig. 7 is a photograph of two Thyssen rotaries in Germany before being enclosed with the brick furnace setting. The steel cylinders are $8^1/_2$ ft. in diameter and 75 ft. long and the capacity of each is about 50 tons per 24 hours. Ten or twelve commercial-scale installations of the rotary type of retort were made in Germany within the last ten years, and have been given a rather thorough commercial trial. The results have been very disappointing. Recent reports are that only one retort is in regular operation working under particularly favorable local conditions. The principal reason for commercial failure of these installations is unsuitability of the semi-coke for domestic use. It is spongy, friable and of low density. The proportion of fines is very large. Also, strongly coking coals adhere to the walls of the retort, reduce heat transmission and lead to overheating and warping of the metal. Another drawback is the dust created by the tumbling coal. Special dust separators are required to throw down the dust from the hot gases before the tar begins to condense. Even with such dust-collecting equipment the tar is likely to contain from 1 to 2 per cent of dust, and a high dust content detracts seriously from the market value of low-temperature pitch, especially when used for briquets.

The latest German development in the horizontal (or rather, inclined) rotary type of retort is the double rotary of the Kohlenscheidung Gesellschaft at Karnap near Essen. As shown in Fig. 8, it consists of two concentric cylinders. The retort is externally heated with producer gas burned in combustion chambers adjacent to the retort. Provision is made for diluting the hot combustion gases with flue gas to provide uniform and closely regulated temperatures around the retort.

The outer retort, approximately 3 meters (10 ft.) in diameter and 25 meters (80 ft.) long, is entirely supported on the inner retort which carries the driving mechanism. This arrangement is said to be a decided structural advantage in that the large stresses and loads come on cold metal, the inner retort never exceeds a maximum temperature of 200 deg. cent. (392 deg. fahr.). The steel shell of the outer retort may go up to 600 deg. cent. (1112 deg. fahr.) without causing an essential injury to the retort. It is claimed that the slow preheating of the coal in the inner cylinder changes the nature of coking coals so that weakly caking coals can be carbonized

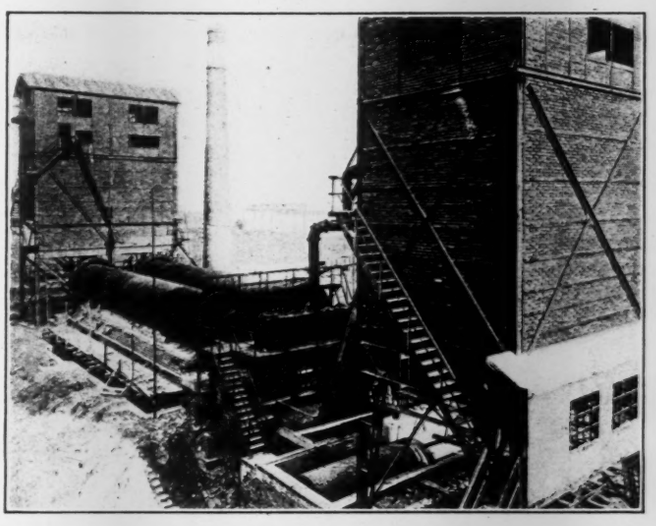

FIG. 7 THYSSEN ROTARY RETORT

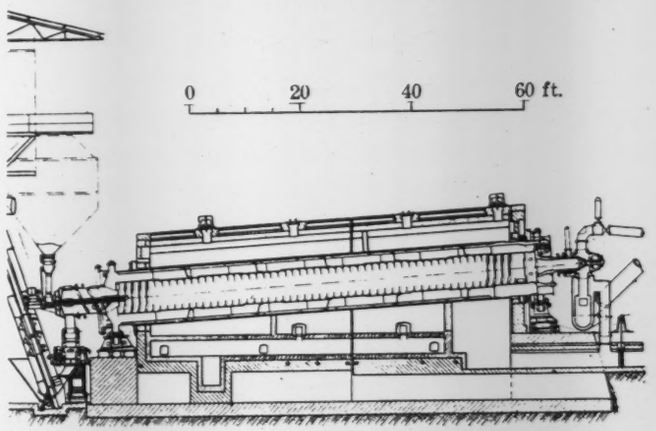

FIG. 8 VERTICAL SECTION OF DOUBLE ROTARY RETORT OF KOHLENSCHEIDUNGS-GESELLSCHAFT

without sticking on the walls of the retort, especially if about 10 per cent of coke breeze is added to the charge.

On visiting this plant in 1924 the author observed several hundred tons of a soft, friable semi-coke on piles near the retort. It appeared too low in density and too friable for a high-grade smokeless fuel, although in a recent article Mr. Cantieny,[9] the manager of the company, states that there is a good demand in Karnap for this fuel for domestic purposes.

It is claimed that due to the double-cylinder feature and to pumping off the evolved gases and vapors countercurrent to the flow of the coal, practically no decomposition of the tars takes place, and the tar yield is 100 per cent of the laboratory yield in contrast to the 60 per cent yield in rotary retorts in which the vapors are removed at the discharge end of the retort.

[7] A. Thau, A New Low-Temperature Carbonization Process for Coal (The Dobbelstein Process), *Fuel in Science & Practice*, vol. 4, 1925, pp. 259–263.

[8] *Colliery Guardian* (London), vol. 131, April, 1926, p. 1023.

[9] G. Cantieny, Der gegenwärtige Stand der Steinkohlenschwelung in Deutschland, *Zeitschrift des Vereines deutscher Ingenieure*, vol. 69, pp. 547–553 (1925). English abstract in *Combustion*, vol. 13, pp. 209–213 (1925).

At the time of the author's visit the retort was shut down for changes in design after an experimental run of five months.

According to the engineers in charge, the principal unsolved problem was to increase the capacity of the unit from about 50 to 100 tons per 24 hours. It was hoped to do this by the introduction of superheated steam directly through the coal in the outer cylinder. Cantieny's recent report[10] states that this object has been accomplished by introducing about 5 per cent of steam superheated to 400–500 deg. cent. at 0.5 atmosphere pressure into the coal in the outer retort. This steam is also said to preserve the tar from decomposition and to prevent condensation on the relatively cool wall of the inner retort. Sixty to eighty tons of coal per day is said to be the present capacity of the retort.

A weakly coking fine slack coal containing 3 per cent water,

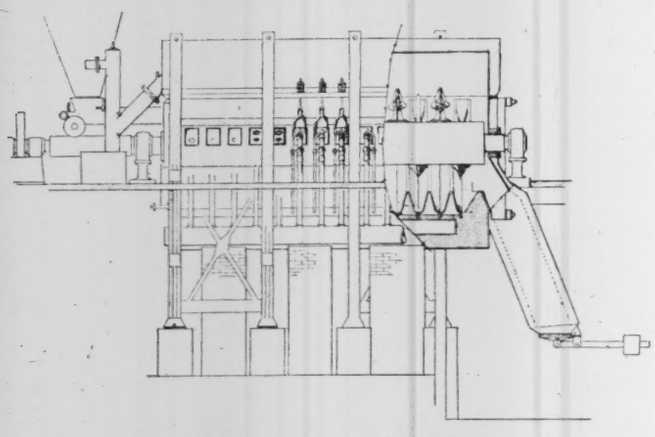

Fig. 9 McIntire Retort—Side Elevation

25.0 per cent volatile matter, 14.8 per cent ash, and 5.8 per cent oxygen yielded per ton of dry coal:

	Per cent
Semi-coke	82.00
Crude tar, water-free	5.05
Light oil scrubbed from gas	0.43
Thick tar	0.48
Gas, cu. ft.	2500

Dr. Reinhardt Thiessen, of the Bureau of Mines, who visited the plant last July (1926) reports that the above-described retort had been taken down shortly before his visit and a new one of improved design was being constructed.

Externally Heated Horizontal Stationary Retort with Internal Stirrer

The McIntire Process. Probably the most highly developed low-temperature process today on a full-size commercial-scale retort is the process of the Consolidation Coal Products Company, at Fairmont, West Virginia. This retort, shown in Figs. 9 and 10, is a modification of the primary carbonization retort of the Smith or "Carbocoal" process installed at Clinchfield, Virginia. The original carbocoal retort was not practical because of breakage of the stirrer arms through resistance of the pasty, fused mass of coking coal, as well as other difficulties. The McIntire retort has solved this problem and has successfully carbonized coal from the Pittsburgh bed—a coaking coal—for considerable periods (2 to 6 months' continuous operation) at the rate of 50 tons per day. The semi-coke produced is partly lumps and partly granular. It is not suitable for domestic fuel without subsequent briquetting and recarbonizing. However, it could be pulverized for powdered-fuel furnaces.

The primary retort is $16\frac{1}{4}$ ft. long and $8\frac{1}{2}$ ft. in diameter. The lower part of the retort consists of V-shaped sections of resistant iron heated by burning gas in the space below. The upper part of the cylinder is removable and made of light boiler plate covered with sil-o-cel. The slack coal is charged continuously into one end of the retort and discharged at the other. The charge is agitated by a central oscillating shaft 30 in. in diameter, carrying arms with paddles. The gas is conducted out of the retort at the coal charging end.

With the coal heated to a maximum temperature of 450 deg. cent. (842 deg. fahr.) the following yields were obtained:

Yields from McIntire Retort per Ton of Coal Charged

Semi-coke (12–14 per cent volatile matter), per cent	75
Gas (875 B.t.u. per cu. ft.), cu. ft.	3000
Crude tar oils (1.080 sp. gr.), gal.	30
Ammonium sulphate, lb.	10

The secondary-stage carbonization is relatively new and this particular retort is to be regarded as an experimental one which is to receive further development, but it does demonstrate the fact conclusively that the briquets can be satisfactorily carbonized; the carbonized product is strong and stands rough handling.

The briquets are easily ignited and burn with a very cheerful, red glow and a short blue flame in an open grate fire. They are evidently of a high degree of reactivity so that combustion is maintained with very low draft; in fact, diffusion of oxygen into the fuel bed is quite sufficient to keep the briquets glowing. They should find a ready market in our eastern cities where people are accustomed to burning anthracite. It cannot be considered a competitor of bituminous or semi-bituminous coal.

There is but little cracking of the tar, judging from the large yields obtained, as the average of some 9 months' operation is

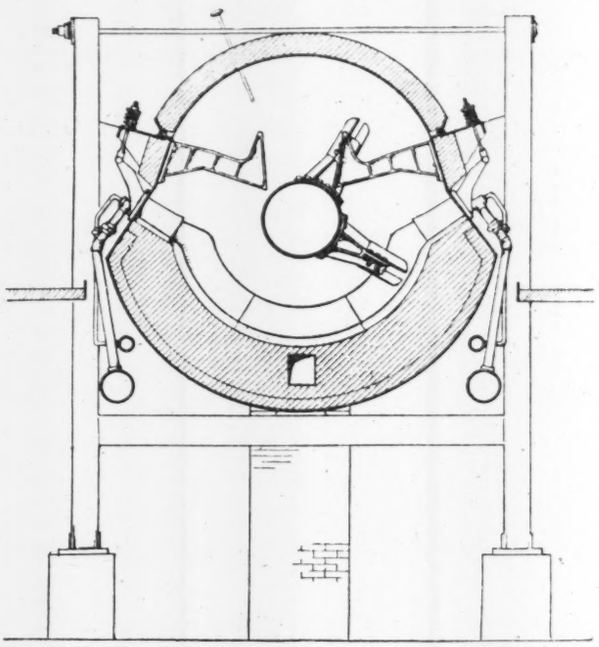

Fig. 10 McIntire Retort—End Elevation

31 gal. of tar per ton of coal, which is practically the same yield as obtained in the small-scale laboratory retort. On the basis of Fischer's definition for low-temperature tar, there would be some decomposition as indicated by the specific gravity being a little above Fischer's limit. Fischer puts it at 0.95 to 1.05. The specific gravity of the primary tar at Fairmont runs from 1.05 to 1.08.

Internally Heated Retorts—Coal in Direct Contact with Preheated Gases or Vapors

Internally heated retorts differ radically from the externally heated types described. These processes are usually continuous—the coal descends in a vertical shaft through which preheated gases or vapors ascend and impart their sensible heat directly to the pieces of coal. Products of combustion, producer gas, water gas, coal gas, superheated steam, or combinations of these gases have all been tried. Generally speaking, this type of retort contains no moving mechanism and is usually of cheaper construction than externally heated retorts. It is not, however, adapted to strongly fusing coal on account of caking and hanging in the retort (except in case of pulverized coal falling through the heated gases where any coal may be used). Likewise the gas cannot circulate uni-

[10] Loc. cit.

formly through the mass if the pieces melt together. Screened lumps of non-coking coal or briquetted fuel are best adapted for retorts of the internally heated type.

The principal disadvantage of introducing hot combustion gases into the charge is the dilution of the distillation products. The resultant large volume of gas of low calorific value must be used at the point of production, and the light oils have too low a partial pressure to be profitably recovered by oil-scrubbing the gas. Superheated steam has the advantage of a greater heat carrying capacity than non-condensable gases, but it in turn involves loss of the latent heat of the steam and extra cost of superheater, satisfactory designs of which are not yet available for the temperatures required. Nevertheless, the low first cost and the simplicity of internally heated retorts have led to many designs based on this principle, some of which are now in large-scale experimental operation.

Coal in Screened Lumps or Briquets Directly Heated by Hot Gases Generated by Air Blown into the Retort

Maclaurin Low-Temperature-Carbonization Process. The Maclaurin retort (Fig. 11) is essentially a large by-product-recovery gas producer in which part of the semi-coke is burned to producer gas, the sensible heat of which carbonizes the descending charge of coal. The experimental producer near Glasgow, Scotland, is of square cross-section, about 45 ft. high and 8 ft. wide at the widest part. The air blast is introduced about 12 ft. above the discharge doors through a large number of narrow ports in opposite side walls, and also by similar ports in a dividing wall which is carried across the center of the retort at the same level. The coke is cooled in the zone below the air ports by steam injected at the discharge doors; part of this steam ascends through the coke and becomes heated and partly decomposed into water gas, then passes upward

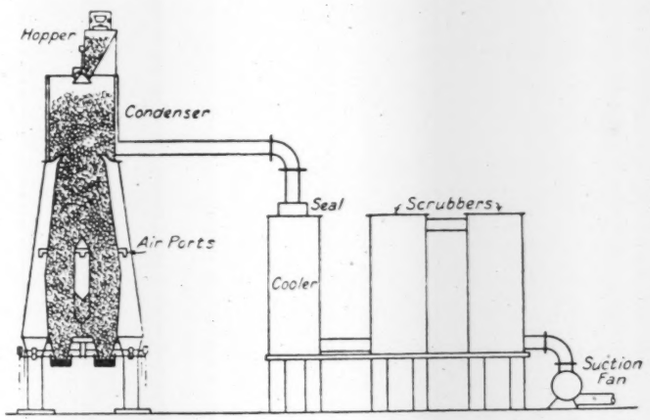

Fig. 11 Maclaurin Carbonizing Plant

and mixes with the producer gas formed in the combustion zone. The raw coal is fed from an elevated hopper through a bell into the top of a cylindrical steel tank 8 ft. in diameter and 10 ft. high, resting on the brickwork at the top of the retort. The tank serves as a condenser for the oils and tars that drain down the side of an inner steel cylinder, which dips into the well formed by a dished flange at the bottom of the tank. From the annular space between the tank and the cylinder the gases are led off to tower coolers and scrubbers.

The capacity of the retort is about 20 tons of coal per 24 hours. The coal should not be strongly coking, otherwise the charge will stick and not descend uniformly; neither will the hot gases be distributed evenly throughout the charge. The retort can be operated for complete gasification or for production of smokeless fuel; the adjustments necessary are in the regulation of the air blasts and the gas outlet valves. The operating temperatures are 750 deg. cent. at the air tuyeres, 200 deg. cent. at the bottom of the steel tank on the top of the brick work, and 60 to 80 deg. cent. in the gas offtake.

The semi-coke produced (Fig. 12) is but slightly fused and of low density; it is not a high-class domestic fuel—nevertheless the Glasgow Gas Corporation has installed a battery of five producers at Dalmarnock aggregating 100 tons of coal per day at the gas plant for the purpose of supplying gas for heating vertical gas retorts and at the same time producing low-temperature coke for smokeless domestic fuel. They expect a yield of from 22,000 to 27,000 cu. ft. of gas of 240 B.t.u. per cu. ft.; from 12 to 17 gal. (U. S.) of dry tar oil, and from 14 to 15 lb. of ammonium sulphate per short ton of coal.

Since this plant is a full-size commercial installation on which reliable cost figures can be obtained, the results will be watched with great interest, especially the popularity of the smokeless fuel. It is a real question whether the public will be willing to pay a sufficiently high price for this fuel to cover the cost of manufacture. Reports on the operation of this plant thus far are that the fuel has

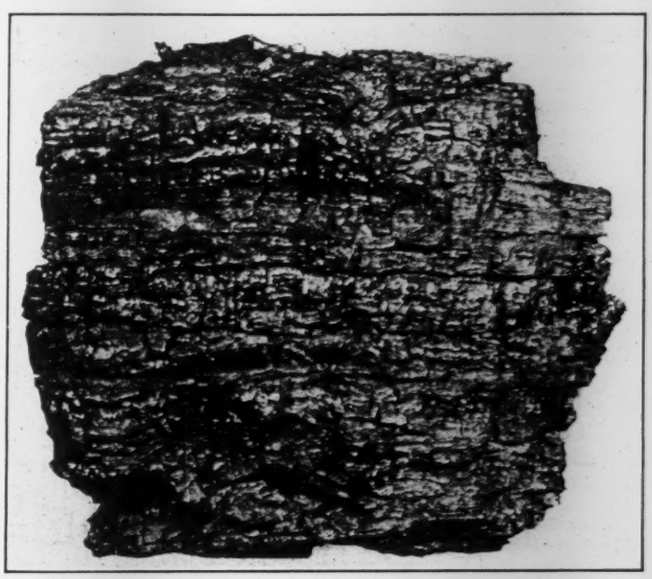

Fig. 12 Semi-Coke Produced by the Maclaurin Process

not met with popular approval and that all operating difficulties have not been ironed out.

Hood-Odell Lignite Carbonizing Process.[11] The Hood-Odell oven for carbonizing lignite is similar in principle to the Maclaurin retort, except that no by-products are recovered. The sole object is to convert brown lignite, which contains from 35 to 40 per cent of moisture, into a stable, usable solid fuel. The oven is cheaply constructed from standard refractory materials. The first cost is low and the throughput per unit is high. About 50 to 60 per cent of the carbonized material can be screened out for direct use as domestic and industrial fuel, while the remainder can be briquetted, forming a high-grade domestic fuel. A modified form of this retort with by-product recovery was built by the Canadian Lignite Utilization Board and successfully operated on Saskatchewan lignite.

Coal Heated by Hot Products of Combustion Generated Outside the Retort

The carbonization of coal or lignite by hot gases generated by blowing air directly into the descending charge has the advantage of simplicity, but there is difficulty in maintaining uniform temperatures across the entire fuel-bed column. German inventors who are particularly interested in careful temperature control to conserve the tar and oil yields of brown coals have favored burning the fuel gas in an external combustion chamber and then circulating these preheated gases through the fuel bed. The Seidenschnur[12] and the Lurgi[13] process are the two best known of this type, and are quite similar in principle, both being designed for lignite or brown coal. A 25-ton-a-day Lurgi unit was recently installed

[11] W. W. Odell, Report of Lignite Carbonizing Experiments Conducted at Grand Forks, N. Dak. in 1922, Bureau of Mines reports of investigations, Serial No. 2441 (1923).

[12] Seidenschnur, Braunkohlenflammkoks, *Braunkohle*, vol. 22, 1924, pp. 352–364.

[13] Octken and Hubmann, Schwelung mit Innenheizung nach dem Lurgi-Verfahren, *Zeitschrift des Vereines deutscher Ingenieure*, vol. 69, 1925, pp. 561–563.

in Greece. It successfully passed a four weeks' acceptance test in March, 1926. Another Lurgi experimental oven is to be installed in Saskatchewan, Canada, for trial on Canadian lignite.

THE PRECARBONIZATION OF FUEL FOR STOKER-FIRED BOILER FURNACES

The precarbonization of coal for by-product recovery in conjunction with stoker-fired boiler furnaces of power plants has been the subject of extended experimentation by Merz and McLellan[14] in England and by the Julius Pintsch Company[15] in Germany. The processes are similar; the carbonizing retort is placed directly in front of the boiler furnace and the semi-coke is discharged on the chain-grate stoker. The coal is carbonized by circulating hot flue gases from the boiler furnace, either alone or with superheated steam in addition, through the descending coal. The coal used must be non-coking, and free from excessive amounts of fines. Coking coals melt together and prevent even distribution of

[14] David Brownlie, Low Temperature Carbonization, *Combustion*, May 26, 1926, pp. 321–326.

[15] A. Thau, Die Verschwelung mit Spülgasen, *Glückauf*, vol. 62 (1926), pp. 701–703.

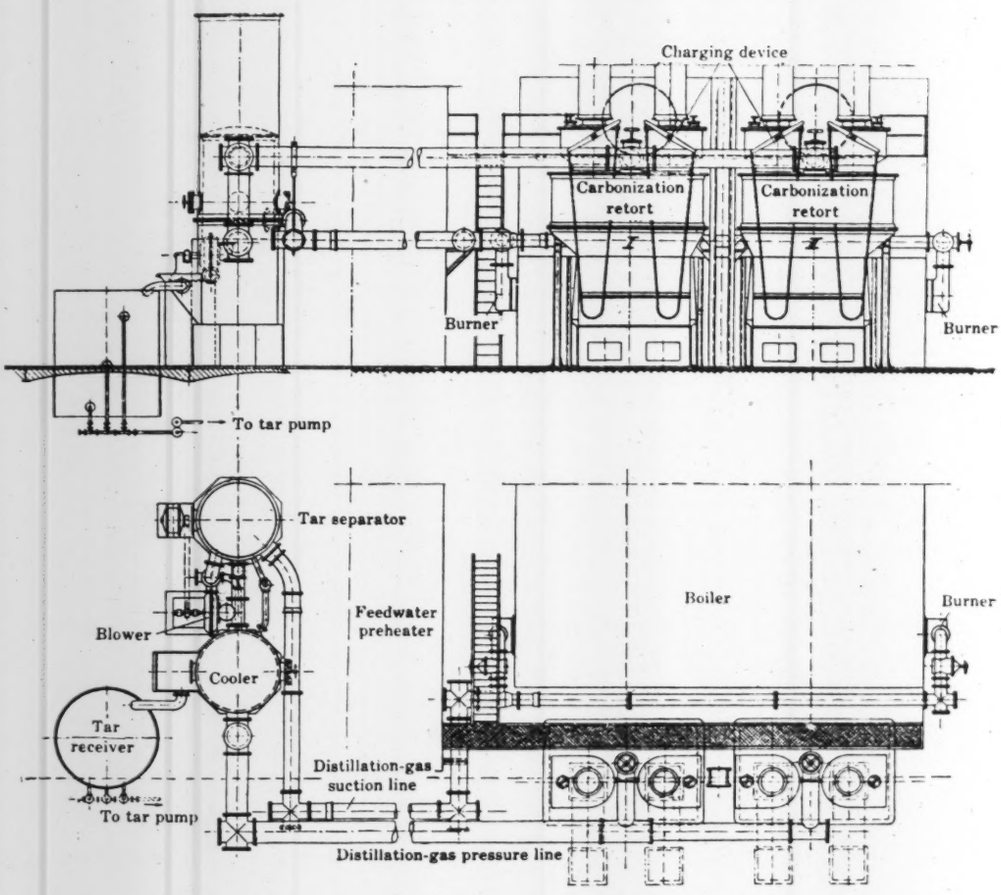

FIG. 14 ARRANGEMENT OF BOILERS AND TAR-SEPARATING PLANT

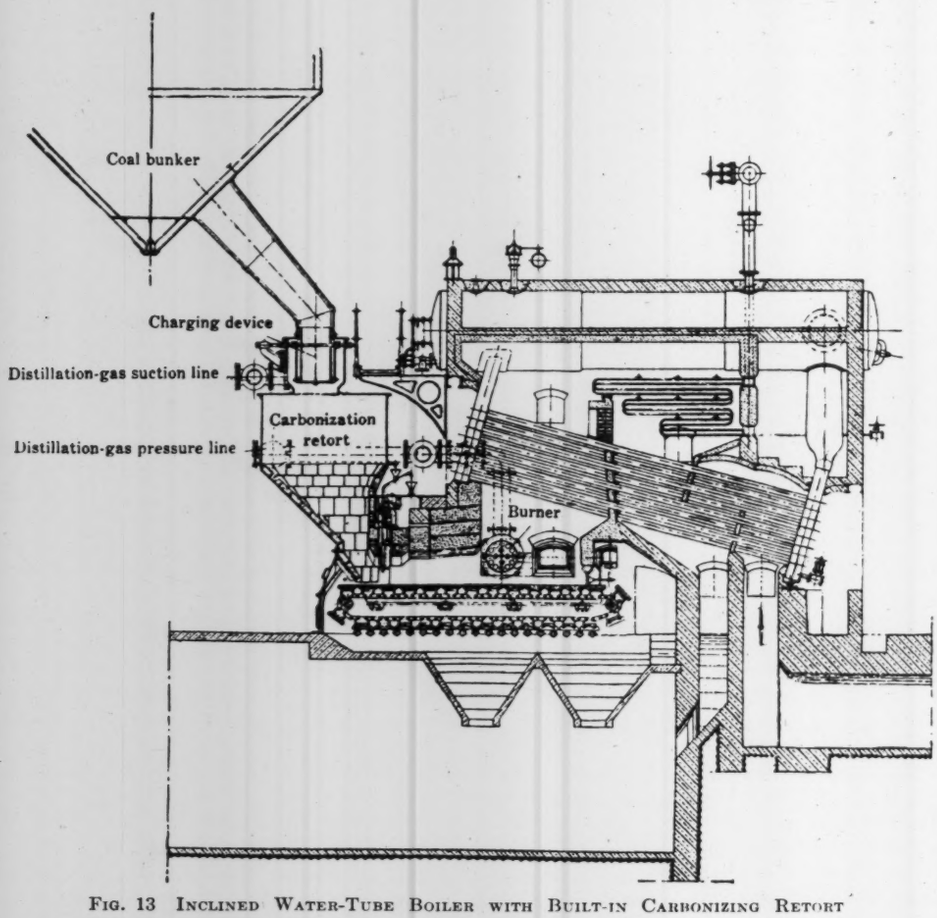

FIG. 13 INCLINED WATER-TUBE BOILER WITH BUILT-IN CARBONIZING RETORT

the heating gases. Fine coal is carried over in the gas current and deposits dust in the tar.

The Merz and McLellan experimental plant is located at the Dunston power station at Newcastle-on-Tyne. It consists of 2 units of about 24 tons capacity each per day. These are directly connected to the furnaces of two Babcock & Wilcox boilers of 4000 sq. ft. evaporating surface each. Tests have shown yields of 16 to 18 gal. of tar per ton of Northumberland non-coking steam coal. No commercial installations have been made of this system as yet.

Thau[16] has reported the following installations of the Julius Pintsch process: 6 units in Upper Silesia operating in conjunction with boilers of 6000 sq. ft. evaporating surface. Waste shaly coal of 27 to 40 per cent ash and of 7800 to 9000 B.t.u. is used. Eighteen to twenty gallons of tar are recovered per ton of coal.

There is one installation in Norway operating in conjunction with a Babcock & Wilcox boiler of 3300 sq. ft. evaporating surface. The fuel precarbonized is a cannel coal from Spitzbergen with 18 per cent ash and a heating value of 11,600 B.t.u. The daily throughput of coal is 23 tons and the tar yield is 27 gallons per ton. Preliminary reports from these plants according to Thau are very promising, provided that the right

[16] Loc. cit.

kind of coal is used, namely, screened and sized non-coking coal from $\frac{1}{2}$ to 6 in. in size. High ash is not objectionable, but the moisture should not exceed 20 per cent. Figs. 13 and 14 show the construction of a Pintsch plant in conjunction with a water-tube boiler.

Fig. 15 shows another German design, that of Hanl. This is an experimental installation. The boiler has 4300 sq. ft. of evaporating surface, and the carbonizer is said to operate satisfactorily with slack coal, due to the internal stirring device, which performs the same function as in mechanically agitated gas producers. In fact, this carbonizer is really a by-product gas producer which does not completely gasify the coal but simply takes out the tar, and then discharges the semi-coke and gas to the boiler. The carbonization is effected by hot products of combustion generated in the producer itself from air admitted to the fuel bed at point *m*.

POWDERED COAL CARBONIZED BY HOT GASES

As the time of carbonizing a lump of coal by hot gases decreases with the size of the lump, it follows that pulverized coal introduced into a stream of hot gases should be carbonized very rapidly.

McEwen-Runge Process. The McEwen-Runge process[17] of the International Combustion Engineering Corporation is based on this principle. A 210-ton-per-day experimental unit has been built at the Lakeside Plant of the Milwaukee Electric Railway and Power Company. The process aims to recover by-products from pulverized coal by an internal heating method such that the carbonized residue can be used directly as pulverized fuel without repulverizing. The heating is so designed that the primary gaseous products can be recovered with minimum dilution by inert heating gases, and they are said to be rich enough for distribution as town gas.

The process is two-stage. It is carried out in two vertical cylindrical retorts (Fig. 16), the first stage being superimposed on the second. The function of the first stage is drying and removal of some water of constitution along with CO_2. The heating is countercurrent; hot combustion gases (700 deg. fahr.) and air containing heat recovered from the carbonized residue are passed in at the base of the first retort where they meet a descending stream of pulverized coal, giving up their heat to it. On passing through the retort these gases contain but little combustible and are rejected. The hot coal falls into a bin from which it is fed mechanically into the second-stage retort. The descending coal is carbonized by (*a*) preheated distillation gases; (*b*) products of combustion introduced into the tower, or (*c*) products of combustion generated within the retort by the admission of a suitable quantity of hot air. The maximum temperature here is 1500 deg. fahr. Auxiliary apparatus includes the usual coolers and scrubbers for removal of the tar from the gas. The process is continuous—requiring 6 min. for both stages. The process goes to the ultimate extreme in rapid heat transfer to the coal and has possibilities of very high throughput in relatively low-cost equipment. But the mechanical difficulties to be solved seem very great, especially in separating the fine dust from the vapors.

The pulverized-fuel-burning people evidently have faith in the pretreatment of pulverized coal and the recovery of by-products in connection with central power generation.

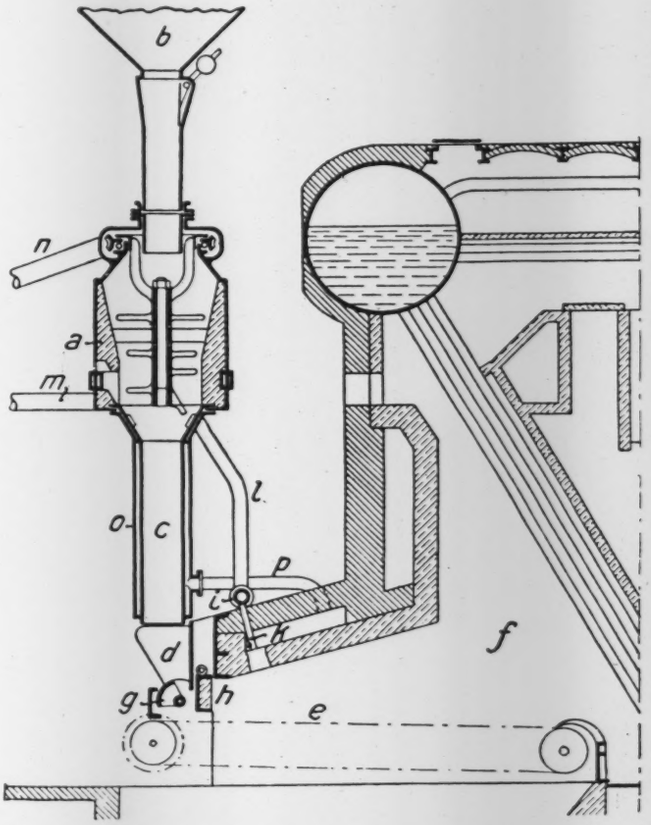

FIG. 15 HANL RETORT COMBINED WITH STEAM-BOILER FIRING

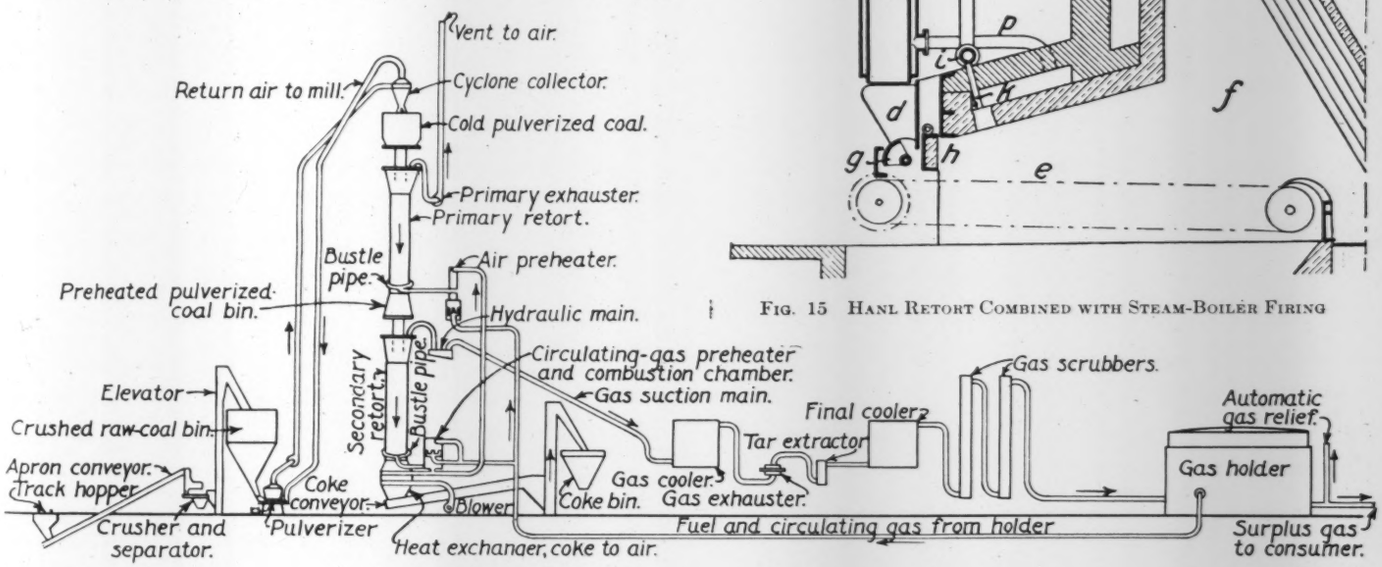

FIG. 16 DIAGRAMMATIC ARRANGEMENT OF MCEWEN-RUNGE PROCESS

COAL HEATED BY PREHEATED GASES CIRCULATING THROUGH A ROTARY RETORT

Laing-Nielsen "Sensible" Heat Process. Laing and Nielsen of England have designed a low-temperature-carbonization process in which the coal is heated directly by hot producer gas, water gas, or reheated coal gas circulated through the interior of a rotating retort.

The cylindrical steel retort is lined with firebrick and lagged on the outside with heat-insulating material. The coal is charged continuously into the upper end of the inclined cylinder, and travels toward the lower end over a system of baffles designed to secure intimate contact with the hot gas that enters at the lower end of the retort.

The experimental retort is about 45 ft. long and 3 ft. in outside diameter. The distilling medium can be (1) combustion products of producer gas, (2) straight non-combusted producer gas carrying

[17] S. McEwen, Carbonization of Pulverized Fuel at Low Temperatures, *Combustion*, vol. 14, February, 1926, pp. 107–110.

the sensible heat of the gas reaction, (3) superheated water gas, and (4) a reheated circulating gas. The temperature of the distilling medium entering the retort is generally about 650 to 700 deg. cent. (1200 to 1300 deg. fahr.), and it leaves the retort at a temperature not below 150 deg. cent. (300 deg. fahr.) It has been found that the temperatures of the coal itself are 100 to 120 deg. cent. (212 to 248 deg. fahr.) below these temperatures. Dust from the distillation gases is separated in cyclone dust catchers, in which no tar is said to condense. The heavy and high-boiling tars are separated in two annular air-cooled condensers. But most of the oil is carried on into the water-tube condensers and the boosting fan which also acts as an efficient oil separator. Leaving there the gas passes through a "P. & A." separator, a final water-tube condenser, and two scrubbing towers through which wash oil can be circulated. The gas, after being freed from its liquid products, can be recirculated, or conducted to wherever it is wanted.

The following figures are based on a series of tests carried out on Barnsley bed coking smalls:

	Coal analysis, per cent	Semi-coke analysis, per cent
Moisture	4.33	Nil
Volatile matter	32.77	10.15
Fixed carbon	55.78	80.95
Ash	7.12	8.90
	100.00	100.00

Yields per Short Ton of Raw Coal

Semi-coke	70.5 per cent
Oil (crude)	19.3 U. S. gal.
Gas	3000 cu. ft. 610 B.t.u. net per cu. ft. at 60 deg. fahr.
Oil:	
From condensers	92.6 per cent = 17.80 U. S. gal.
From gas scrubbing	7.4 per cent = 1.43 U. S. gal.

Standard Fractionation of Condenser Oil (Engler)

Fraction	Per cent by weight	Specific gravity
0 to 170 deg. cent.	0.3	0.860
170 to 230 deg. cent.	13.1	0.945
230 to 270 deg. cent.	19.5	0.977
270 to 360 deg. cent.	31.2	0.987
360 to 400 deg. cent.	18.5	1.026
Pitch coke	15.2	...
Oil from gas scrubbers	..	0.822
Water in crude oil after 24 hr. settling	3.3 to 5.5 per cent	
Tar acids in crude oil	42 per cent	
Sulphur in crude oil	0.32 per cent	
Flash point of Diesel fraction, 270 to 300 deg. cent.	195 deg. fahr.	

Thermal Balance

Total heat in raw coal on dry basis = 291 therms
Total heat in raw coal as received = 272 therms

	Per cent		Therms
Recovered as semi-coke	70.5	=	191.3
Recovered as oil	10.4	=	28.4
Recovered as gas	8.3	=	22.7
Total recovered, gross	89.2	=	242.4
Heat requirements in process:			
Moisture, 4.33 per cent			Therms
Heating, evaporation, and superheating.		=	1.175
Semi-coke, 70.5 per cent			
Leaving at 550 deg. cent.		=	4.025
Oil, 10.4 per cent			
Heat of formation, etc.		=	0.925
Distillation gas:			
Useful heat per cu. ft. between 650 and 150 deg. cent. = 15.85 B.t.u. per cu. ft. = 0.0001585 therm.			
Total quantity of gas circulated = 44,000 cu. ft., leaving at 150 deg. cent.		=	2.080
Radiation losses in retort, etc. and difference		=	0.849
			9.054
Total heat in 44,000 cu. ft. of gas at 650 deg. cent.		=	9.054

This heat was provided by gasifying coke in a gas producer and burning the producer gas with secondary air. The overall efficiency of the combustion is 50 per cent. Hence therms required as coke = 9.054 × 100/50 = 18.1 therms = 6.64 per cent. The net heat recovery is therefore 242.4 — 18.1 therms = 224.3 therms or 82.56 per cent.

Superheated-Steam Processes

At first thought it would seem that superheated steam would be the best heat-transfer medium for low-temperature carbonization. It has a relatively high specific heat; it does not dilute the distillation gases; and it permits the recovery of the light oils from the gases. However, there are two very strong objections which have prevented the development of any promising process using steam alone. These are: (1) The large heat losses in the latent heat of vaporization, combined with a large and costly condensing system, and (2) the cost of superheating equipment that will resist the strong corrosive action of steam superheated to the degree necessary for carbonization.

The auxiliary use of a small quantity of steam in other processes has been of some advantage in distributing heat through the charge and in increasing ammonia yields, as, for example, in the Scottish oil-shale process.

Comparison of Various Systems

It is evident from a consideration of the many different processes that have been and are being tried experimentally that no outstanding single method has yet met with unqualified technical success. Each has its peculiar problems yet to be solved, although a number have shown promise under certain favorable conditions. The processes that depend on internal heating by combustion gases are simpler and require less capital expenditure per ton of coal carbonized, but they are limited to non-coking, weakly coking coals or briquetted coals; also the gas is of low calorific value and the light oils are not recoverable from the diluted gas. However, such processes are promising for future development in combination with large central-station power plants or industries using large quantities of gas of low heating value, at such future time when diminishing petroleum supplies create a demand for low-temperature fuel oils.

The higher-cost processes using externally heated retorts will probably find their most advantageous field in making relatively high-priced smokeless domestic fuel from a cheap non-coking or poorly coking coal in connection with a market for high B.t.u. gas. These processes also yield several gallons of light oil that is not to be had from internally heated processes. Local economic conditions and the type of coal available are important factors governing the selection of the most suitable process.

Products of Low-Temperature Carbonization

The quantity and quality of the carbonization products of coal depend upon the type of coal used and the heat treatment it receives in the process. High-temperature processes produce hard cellular coke and crack the primary tars into fixed gases, aromatic light oils, and viscous tars containing phenols, cresols, anthracenes, naphthalene, and other aromatic compounds. Low-temperature processes produce softer semi-coke, which retains 7 to 15 per cent of volatile matter and also produce uncracked and but slightly decomposed primary tars and oils containing paraffins, naphthenes, cresols, xylenols, and higher phenols. The gas volume obtained is only one-fourth to one-third that obtained in high-temperature coking, but has almost twice the calorific value per cubic foot. The quantity of light oil suitable for motor fuel is about the same from both processes; the composition, however, is quite different. The low-temperature product contains saturated and unsaturated paraffins, hydrocarbons, naphthenes, and complex aromatic hydrocarbons; while the high-temperature process yields benzol, toluol, and xylol.

The total low-temperature tar yield is from 2 to $2^1/_2$ times that obtained at high temperature, but the ammonia yield is only one-third to one-half as much.

These comparisons apply to externally heated retorts. Internal heating dilutes the light oil vapors to a point where recovery is impracticable by present methods and produces large volumes of gas of low calorific value.

Table 2 gives approximate yields of high-temperature and the two main types of low-temperature processes—namely, externally and internally heated retorts.

An analysis of these yields shows that the only increased by-product return is the 15 gal. more of tar oil per ton of coal carbonized over that now being recovered in standard by-product ovens.

TABLE 2 APPROXIMATE COMPARATIVE YIELDS OF HIGH- AND LOW-TEMPERATURE-CARBONIZATION PROCESSES

	High-temperature carbonization	Low-temperature carbonization	
	By-product coke-oven	Externally heated retort	Internally heated retort[a]
Coke, per cent	60–70	70–80	60–75
Volatile matter in coke, per cent	1–2	7–15	7–15
Gas, cu. ft., ton	11000–12000	3000–5000	20000–50000
Calorific value of gas, B.t.u., cu. ft.	520–580	800–1000	150–250
Tar, gal	10–12	20–30	18–20
Specific gravity of tar	1.19	1.07–1.09	1.02–1.07
Light oil for motor fuel, gal	2.5–3.0	2.5–3.0	None
Ammonium sulphate, lb	25–30	10–12	12–18

[a] By hot combustion gases.

As the price of this tar is determined by the prevailing price of fuel oil, that is, about 5 cents per gallon—the additional credit is only 75 cents per ton of coal. Against this credit must be charged a lower ammonia return of approximately 35 cents per ton of coal and a lower yield of gas. Obviously the by-products of low-temperature carbonization do not today afford a much greater financial return, than existing methods of high-temperature carbonization.

IMMEDIATE FUTURE OF LOW-TEMPERATURE-CARBONIZATION PROCESSES

Where, then, is the possibility of profitably engaging in the low-temperature carbonization of coal in America under present economic conditions? This is a very difficult question to answer. Fuel technologists experienced in gas and coke manufacture are as a rule very skeptical of any low-temperature process being commercially successful in the near future. They point out that the principal product of these processes is semi-coke. Therefore this product must find an adequate market at a sufficient price to make the process profitable in competition with gas and by-product-oven coke. It is not likely that any greater price can be secured than the prevailing price of high-temperature coke sold for domestic purposes. Furthermore this low-temperature coke is too friable and porous from many of the proposed processes to be directly used as a domestic fuel. It must first be briquetted, and this operation adds further cost to the product.

In reply to these objections, it is admitted that the commercial success of low-temperature carbonization of coal in the near future must depend mainly on the sale at an adequate price of the solid product—smokeless fuel—rather than on the liquid and gaseous by-products. The by-products are important contributing factors, but they cannot carry the entire cost of processing the coal under present competitive prices of petroleum fuels.

However, it does not follow that low-temperature carbonization cannot be developed to make a high-grade fuel from low-priced non-coking coals. There is relatively little coking coal in the central and western states. These non-coking or poorly coking coals are not suitable for by-product coke ovens. Processing these coals affords a fairly large margin between cost and selling price of the processed fuel, so that it seems possible to work out a low-temperature process which can compete with high-temperature processes, requiring more expensive raw material in supplying the smokeless-fuel requirements of this region.

A Mercury Compressor Evolved from the Archimedes Screw Pump

By J. G. DeREMER,[1] NEW YORK, N. Y.

This paper contains brief record of the development of a novel type of gas compressor which functions on the principle of the Archimedes helical pump, using mercury as a compressing liquid.

The compressor as now developed consists of a steel cylinder mounted to swing in a circle as a conical pendulum, the wrist-like motion at the top being accommodated by two flexible metallic tubes which conduct the gas into and out of the compressor.

The mercury flowing through a helical passageway within the cylinder picks up separate volumes of gas, and compresses them to any desired value without the use of any internal moving parts whatsoever. Thus the compressor requires no lubricant in contact with the gas or mercury.

Two applications of the compressor to refrigeration practice are described, and the general characteristics of the compressor performance are set forth.

A NUMBER of years ago the author's attention was drawn to the demand for a small refrigerating machine suitable for household and small commercial use. An investigation of the art as it then stood revealed the following more or less serious

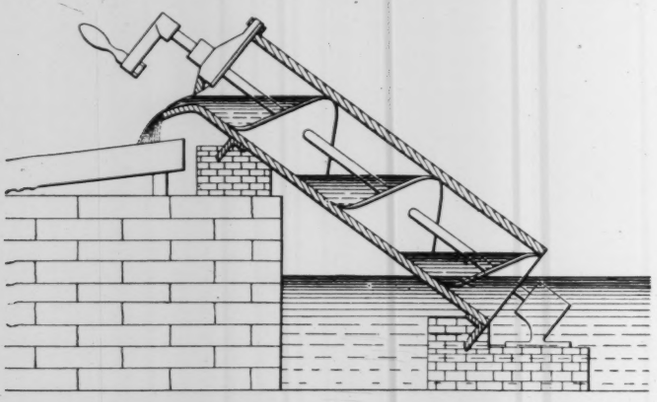

FIG. 1 ORIGINAL ARCHIMEDEAN SCREW PUMP

difficulties necessary to be overcome before a compression-type machine could be made really satisfactory. These were:

1 Gland or stuffing-box leakage
2 Lubrication in the presence of the refrigerant
3 Loss of lubricant from the compressor to the evaporator
4 Leaking at discharge valves, and noise in their operation
5 The wear of internal parts reducing the volumetric efficiency
6 The accuracy of workmanship required to insure high efficiency during a long life
7 In the water-cooled types, the prevention of excess pressures when the water failed
8 If air-cooled, the loss at high temperatures from valve and piston leakage and clearance.

These items all involved the compressor, and it is the purpose of this paper to describe a novel type of compressor developed during the past ten years, which avoids all of them.

HISTORICAL

The fundamental principle upon which this compressor is based is attributed to Archimedes of Syracuse (287–212 B.C.). He is said to have developed a helical-screw pump for the purpose of removing water from the hold of a large ship that had been built by King Hiero II of Syracuse. (Encyclopedia Brittanica.)

Archimedes was the most celebrated mathemafician of antiquity, and his famous saying in regard to the principle of the lever, which he discovered, is exemplified in the seal of this Society.

His helical pump is mentioned in Plutarch's Lives, and it has been used for more than two thousand years as a means of lifting water.

The principle is also said to have been used in Southern France

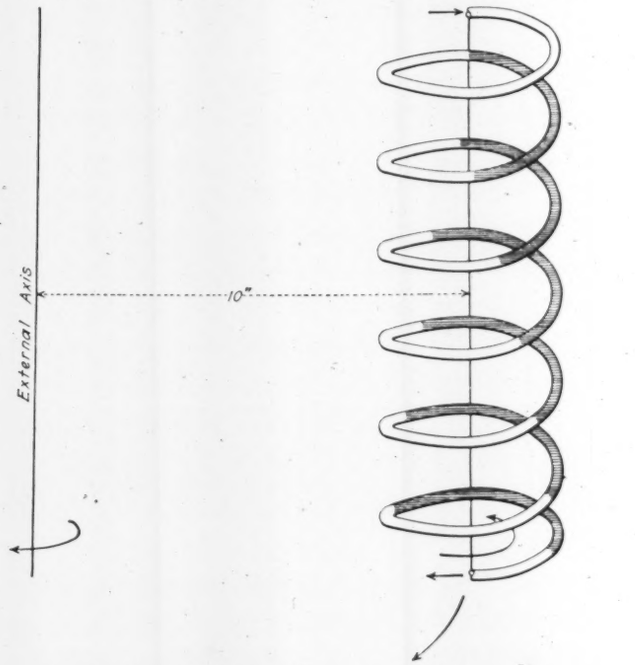

FIG. 2 HELICAL TUBE ROTATED AROUND EXTERNAL AXIS TO DEVELOP HIGH PRESSURE

to supply air to blacksmiths' forges. It is this latter application which has been taken advantage of in the compressor to be described.

So far as the author is aware, no modern application of this fundamental principle has been made until the last decade.

ELEMENTARY GRAVITY COMPRESSOR

If a tube is coiled up into a helix or corkscrew and then rotated with its axis inclined to the horizontal so that the open lower end will dip into a liquid during a part of each revolution, the liquid will be carried up through the tube and discharged at the upper end. This is the original Archimedean helical pump. (See Fig. 1.)

The blacksmith's-forge application takes advantage of the fact that not only is the liquid carried up the tube in separate masses or plungers, but the air imprisoned between each two such liquid plungers is also carried up the tube and discharged at the upper end.

If now the upper end of such a tube be rigidly connected with a rotatable tank or receiver, both the air and the liquid will accumulate in the receiver with a resulting increase in pressure. Provision can be made for returning the liquid to its original position, so that the air alone will remain in the tank or receiver, where, if the operation is continued, it will accumulate a pressure limited only by the ability of the successive liquid plungers to force more air up the tube.

CENTRIFUGAL COMPRESSOR

As will be readily appreciated, the pressure limit in the foregoing illustration is very low, even if it is assumed that the liquid is one having a high density, such as mercury. It is possible, however, to increase the effective pressure to any desired amount by carrying the entire coil around an external axis at a considerable speed.

[1] Consulting Engineer, Savage Arms Corporation. Mem. A.S.M.E.

For presentation at the Annual Meeting, New York, December 6 to 9, 1926, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. All papers are subject to revision.

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Thus, if the helical tube is carried around another axis at three hundred revolutions per minute, and the radial distance from this new, or primary, axis to the coil axis is ten inches, then the effective pressure produced by the liquid in the coil will be increased twenty-five times. (See Fig. 2.)

The arrangement of the parts to accomplish the foregoing is shown in Fig. 3. A helix is cut on a round steel block *A* as a double or triple thread, and over the thread is shrunk a tube *B*. Within the helix block, and attached to its upper end, is a tube *C* which extends down below the end of the helix block into the high-pressure chamber *D*. This tube returns the mercury to the low-pressure chamber *E*. A discharge tube *F* welded into the mercury return tube *C* carries off the compressed gas from the concentric space *G*. The suction line is the main supporting tube *H*. The unit may be mounted in a gimbal or universal joint at the top, and carried around the vertical external axis in a circle by an arm at the lower end. The cylinder makes an acute angle with the vertical axis, the motion thus being that of a conical pendulum. The suction and discharge lines are shown in Fig. 3 as rubber hose.

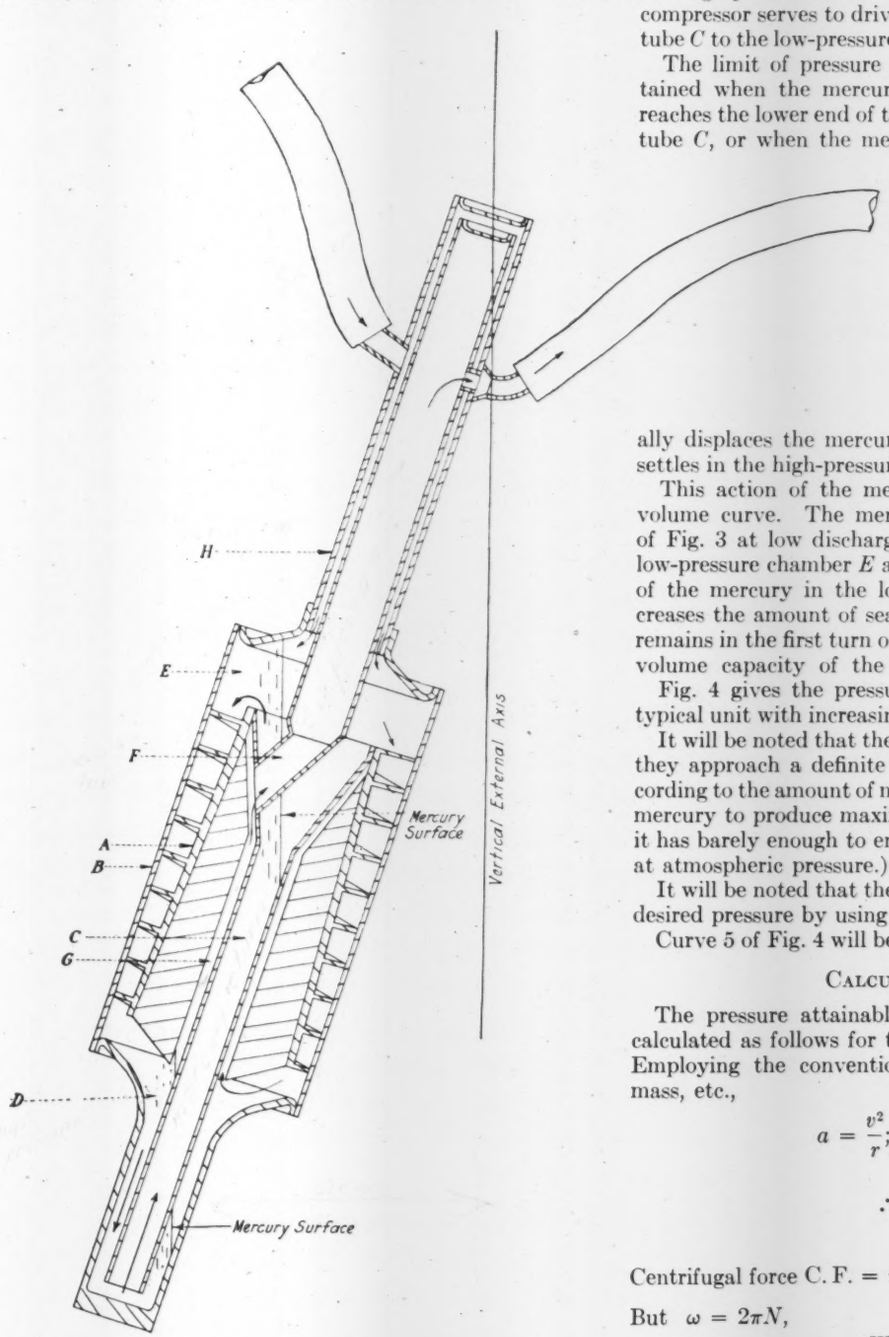

FIG. 3 MERCURY-COMPRESSOR CYLINDER OF CONICAL-PENDULUM TYPE USING RUBBER-TUBING GAS CONDUITS

When supplied with a suitable quantity of mercury and so rotated, the mercury will establish the positions shown in Fig. 3, and its flow will be as indicated by the heavy arrows. The gas flow will be as shown by the light arrows.

The separation of the mercury from the gas is accomplished in the high-pressure chamber *D*, and the pressure in this end of the compressor serves to drive the mercury radially inward through the tube *C* to the low-pressure chamber *E*.

The limit of pressure which the compressor will develop is attained when the mercury level in the high-pressure chamber *D* reaches the lower end of the tube *C*, thus letting the gas blow up the tube *C*, or when the mercury is blown back through the several turns of the helix. Obviously, the design is worked out to balance these two values as closely as possible.

When first starting, the mercury stands up in the annular space *G* to a level equal radially to that in the low-pressure chamber *E*, else it would not tend to flow back through the tube *C* and into the chamber *E*. As the gas pressure accumulates in the high-pressure side of the compressor, it gradually displaces the mercury in the annular space *G* until the level settles in the high-pressure chamber *D*, about as shown in Fig. 3.

This action of the mercury results in an interesting pressure-volume curve. The mercury which lies in the annular space *G* of Fig. 3 at low discharge pressures is ultimately forced into the low-pressure chamber *E* as the pressure rises. This raises the level of the mercury in the low-pressure chamber *E*, and thereby increases the amount of sealing in the helix. Less volume therefore remains in the first turn of the helix to be filled with gas, so that the volume capacity of the compressor is correspondingly reduced.

Fig. 4 gives the pressure-volume curves (1, 2, 3, and 4) for a typical unit with increasing quantities of mercury.

It will be noted that the volumes at low pressure are low, but that they approach a definite maximum at some value of pressure according to the amount of mercury present. (Curve 1 has insufficient mercury to produce maximum volume at any discharge pressure—it has barely enough to enable the compressor to establish volumes at atmospheric pressure.)

It will be noted that the volume can be made a maximum for any desired pressure by using the required amount of mercury.

Curve 5 of Fig. 4 will be discussed later.

CALCULATION OF PRESSURES

The pressure attainable in this type of compressor is readily calculated as follows for the condition where the tube *C* limits it: Employing the conventional notation for acceleration, velocity, mass, etc.,

$$a = \frac{v^2}{r}; \quad v = r\omega; \quad v^2 = r^2\omega^2$$

$$\therefore a = \frac{r^2\omega^2}{r} = r\omega^2$$

$$\text{Centrifugal force C. F.} = ma = \frac{W}{g}a = \frac{W}{g}r\omega^2$$

But $\omega = 2\pi N$,

$$\therefore \text{C. F.} = \frac{W}{g}r4\pi^2N^2 = \frac{4\pi^2}{g}WrN^2$$

$$= 1.227\ WrN^2 \quad (r = \text{feet})$$

$$= \frac{1.227}{12}\,Wr'N^2 \quad (r' = \text{inches})$$

$$= \frac{Wr'N^2}{9.77} = \frac{Wr'N^2}{10} \text{ (approx.)} \ldots\ldots\ldots\ldots [1]$$

where r^1 = radius in inches
W = weight in pounds
N = revolution per second.

Referring to Fig. 5, a centrifuge column of liquid one square inch in area, having radial distances to outer and inner ends of r_1 and r_2, respectively, will develop pressures at the outer end as follows:

For a small lamina dr,

$$d\text{C.F.} = \frac{Drdr.N^2}{10}$$

where D = density
dr = differential lamina
r = radius of differential lamina

Integrating between r_1 and r_2 the whole tube will develop a pressure

$$\text{C.F.} = \int_{r_2}^{r_1} \frac{DrdrN^2}{10} = \frac{DN^2}{10}\left[\frac{r^2}{2}\right]_{r_2}^{r_1}$$

$$= \frac{DN^2}{10} \times \frac{(r_1^2 - r_2^2)}{2} = \frac{DN^2}{10} \times \frac{(r_1 + r_2)\ (r_1 - r_2)}{2}$$

$$= D(r_1 - r_2) \times \frac{r_1 + r_2}{2} \times \frac{N^2}{10} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

$$= \frac{W\ R\ N^2}{10} = P$$

where W = whole weight of liquid
R = mean radius of column
C. F. = centrifugal force = P = pressure per sq. in., since area of tube was taken as 1 sq. in.

Where the tube is inclined to the main rotation axis, the weight of liquid W is necessarily taken as the radial difference between the outer and inner surfaces of the liquid in the tube multiplied by the density.

An illustration will serve to show the relative values of the factors involved in producing 60 lb. pressure with mercury.

Let r_1 = 8 in.
r_2 = 4 in.
diff. = 4 in.
} R = 6 in. = average radius of liquid

W = 2 lb.; density of mercury = 0.5 lb. per cu. in. (approx.)

$$\therefore P = \frac{WRN^2}{10} = \frac{2 \times 6 \times N^2}{10} = 60$$

$$N^2 = \frac{600}{12} = 50; \quad N = 7.07; \text{ or r.p.m.} = 425$$

It is apparent from Equation [2] that the pressure varies not only with the square of the speed, but very nearly with the square of the outer radius; i.e., exactly so if inner radius $r_2 = 0$.

It has been found that with a $3^1/_2$-in.-diameter helix, one turn has a pressure limit approximately equal to one radial inch of the mercury return tube. In the foregoing illustration the four radial inches of mercury-return tube will require four turns of helix to produce the same maximum pressure.

It will be apparent that this compressor cannot exceed these pressure limits unless the speed of operation is increased, and that the danger from excess pressures, as e.g., in refrigeration practice, is avoided.

Features of Design

The double-thread helix used in these compressors has a varying volume per turn obtained by decreasing the thread depth in the direction of the mercury and gas flow. This is done to give the individual turns of the helix greater compressing power due to the relatively greater volume occupied by the mercury as it progresses through the helical passage. Thus, if the volume reduction is two to one and the mercury seals off one-third of the first turn of the helix, it will seal two-thirds of the last turn. Correspondingly, the gas volume will be reduced from two-thirds of the volume of the first helix turn to one-third the volume of the last helix turn, giving a compression ratio of four to one.

The angular arrangement affords opportunity to return the mercury from the high-pressure end of the helix cylinder to the low-pressure end, without loss in energy other than the friction incident to its flow through the mercury return tube. The mercury is elevated radially toward the main axis of rotation, thereby recovering the rotary potential energy which it gives up in slipping down through the helix later.

The position affording the greatest pressure difference in the mercury return tube would be when the cylinder axis makes an angle of 90 deg. with the main rotation axis, like the tube of Fig. 5. However, at this angle the helix would cease to function for obvious

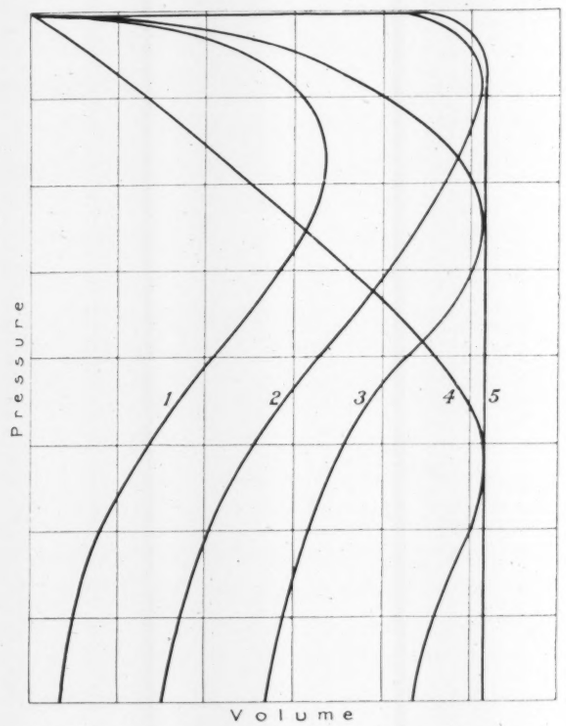

Fig. 4 Pressure-Volume Curves of Mercury Compressor
(Curves 1, 2, 3, and 4, without inner helix; curve 5, with inner helix.)

reasons. On the other hand, the position for maximum pressure development in the helix is that shown in Fig. 2, where the helix axis is parallel with the main rotation axis. In this position, however, it is apparent that the mercury return tube would not sustain any pressure difference between its high-pressure and low-pressure

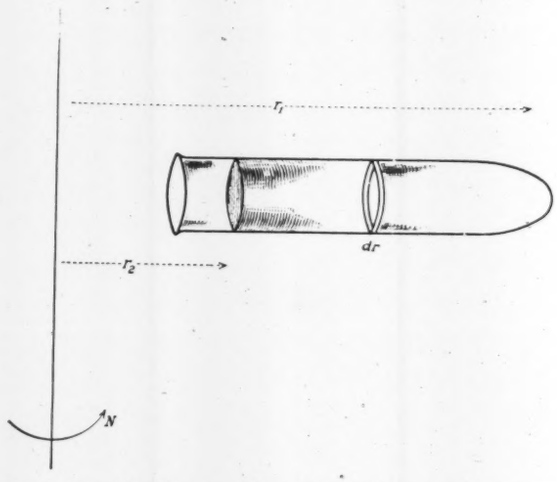

Fig. 5 Centrifuge Tube to Illustrate Pressure Calculations

ends. Angles midway between these extremes are therefore the desirable ones for balanced operation.

For purposes of economy of mercury, and to get lightness of construction, it has been found advisable to place an inner helix within the lower end of the main helix and pitched so as to keep the mercury out of the annular space G, Fig. 3. This space may then be made as large as possible, thus reducing the metal weight, and as the mercury cannot remain in this space once the machine is brought

up to speed, the quantity of mercury is reduced by the amount that would otherwise fill the annular space G.

This inner helix has a very important bearing upon the pressure-volume characteristic of the compressor. Since the mercury cannot enter the chamber above the inner helix, the mercury level in the low-pressure chamber E does not vary as the pressure changes, and thus the characteristic becomes a vertical line as shown at 5, Fig. 4.

The change in characteristic produced by this inner helix is very pronounced, as will be apparent from comparison of the curves of Fig. 4. Curve 5 requires only the amount of mercury of curve 2, and yet produces full volumes at all pressure up to the limit.

Fig. 6 shows the mercury cylinder equipped with the inner helix. This is the design now being manufactured, and which gives the characteristic shown at curve 5, Fig. 4.

APPLICATIONS OF MERCURY COMPRESSOR—FLEXIBLE-TUBE DESIGN

There are two interesting ways to utilize a compressor of this type. Since the motion of the mercury cylinder is that of a pendulum, swinging a circle, it is possible to attach flexible tubes to the neck of the cylinder at the point of its minimum motion and thus connect any remote stationary system desired.

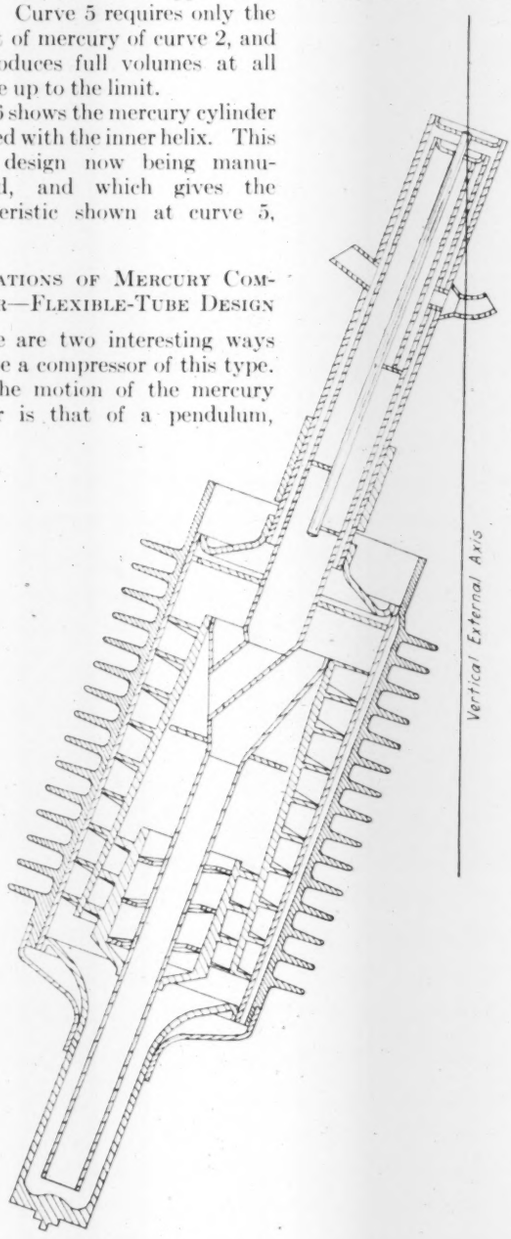

FIG. 6 SECTION OF COMMERCIAL MERCURY COMPRESSOR SHOWING MAIN HELIX AND INNER HELIX

For laboratory and testing purposes, in developing this compressor, various types of rubber hose used in automobile practice sufficed.

For refrigeration purposes or where gases are to be compressed which attack rubber, a flexible metal coiled tube has been developed to join the mercury cylinder with the remainder of the refrigerating system.

As originally developed, the coils were wound in spiral form, both the suction and discharge lines being coiled in one plane. This plane was horizontal and intersected the point where the vertical axis of the machine and the axis of the mercury cylinder meet.

In later designs the spiral flexible tubes were arranged in two layers, in order to reduce the diameter and avoid contact with the tubes in operation. These coils are shown in Fig. 7.

These flexible tubes also take the torque or twist set up by the bearing friction and pneumatic pressure against the mercury plungers, as well as by the mercury friction in the cylinder and helix.

The development of these flexible metallic tubes has been a special metallurgical problem, which will be covered by a separate paper at an appropriate time.

RIGID-ELEMENT DESIGN

Another method of utilizing this compressor for refrigerating purposes consists in extending the mercury-cylinder neck up past the point of intersection of the two axes of the machine, attaching thereto a chamber which becomes the refrigerant storage space and expansion surface of the refrigerating machine. Fig. 8 shows this application in a horizontal machine which was really developed earlier than the flexible-metallic-tube type of machine.

FIG. 7 COMPLETE MERCURY CYLINDER SHOWING FLEXIBLE GAS CONDUITS AND ALUMINUM RADIATOR

Here the mercury cylinder, together with the evaporator storage tank, constitute a sealed bottle within which no moving parts whatsoever are required.

An arrangement of a tube on the extended axis of the cylinder element, and thus concentrically within the evaporator chamber, provided a means to utilize a rotary mercury seal for the expansion valve.

Suitable internal-tubing arrangement was provided to insure that this tube should be properly filled with mercury every time the machine started up.

The necessary radiating surface, both for condensing the gas after compression and for evaporating it after the liquid has passed through the mercury-seal valve, is provided by external tubing coils wound around the mercury cylinder and the evaporator cylinder, respectively.

The condenser coil is suitably joined to the discharge tube of the mercury cylinder.

In Fig. 8 the right-hand end shows the condenser coil wound around the mercury cylinder, while the left-hand end shows the expansion coil wound around the evaporator storage chamber. This end of the refrigerating element rotates within a heat-insulated compartment, and is sprayed with brine by the small circulating pump mounted at the left end of the shaft.

As constructed, this machine was built and operated some period of time using a water spray over the condenser and a brine spray over the expansion coil. In this way its operation proved to be entirely according to expectation.

The machine still has the original charge of gas and mercury placed in it about six years ago.

This machine suffers from the necessity of providing flexible insulation at the point where the neck of the operating element and the mounting shaft pass from the warm to the cold chamber. It also suffers from the necessity of carrying both its hot and cold radiating surfaces on the rotary mounting.

The rigid element of this machine, being gear-driven as shown in Fig. 8, had the advantage of enabling the mercury cylinder to be operated at speeds independent of the frame speed; thus, volume or pressure can be varied independently, which is not the case with the flexible-coil machine.

This rigid sealed-element type of machine also possesses an interesting theoretical possibility in that the bearing loads set up by the usual centrifugal forces may be completely neutralized by mounting a suitable flywheel on the element to develop gyroscopic forces in exact opposition to the centrifugal forces.

As in the case of the gyrocompass, a flywheel mounted on the rigid element of Fig. 8, and rotated in proper relation with respect to the mounting-frame rotation, would tend to place the element in parallel relation with the frame axis. The centrifugal forces, on the other hand, tend to throw the element to a position perpendicular to the frame axis. The application of this idea, however, is clumsy.

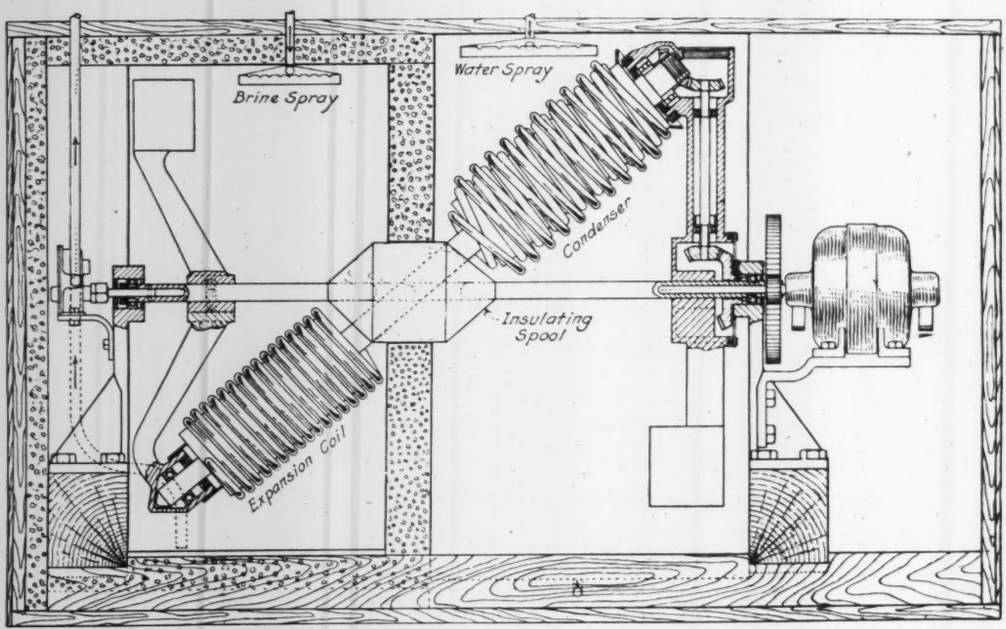

FIG. 8 HORIZONTAL RIGID-ELEMENT TYPE OF REFRIGERATING MACHINE

ADVANTAGES OF FLEXIBLE-TUBE TYPE

The machine as finally developed for commercial use is of the type using the flexible metallic tubing.

This compressor possesses a number of distinct advantages over the usual type:

It permits operation of a refrigeration system under conditions of high vacuum without accumulation of air, since the entire system may be definitely sealed.

It requires no lubrication in contact with the gas compressed.

The compressor suffers no reduction in capacity through prolonged use, as there is no leakage around the mercury pistons.

Since every mercury piston delivers its full quantity of gas to the high-pressure chamber of the cylinder, the compressor suffers no clearance loss nor any reëxpansion loss, and therefore has the same volumetric capacity at all pressures up to the maximum.

As above stated, the compressor has a definite maximum pressure which it will not exceed at constant speed. This affords a valuable safety provision in refrigeration practice.

This compressor affords an unique opportunity to cool the gas during compression, by radiating heat through a radiator attached to the cylinder, as shown in Figs. 7 and 9. The temperature of the discharging gas is substantially that of the saturated vapor at the pressure developed, all superheat apparently being radiated during compression.

This heat radiation is accelerated by the facility with which mercury picks up heat and radiates it to the metallic cylinder as it travels along.

The specific heat of mercury is very low (0.033), hence but little heat is necessary to raise its temperature enough for it to pass the heat along to the outer cylinder walls.

THE COMMERCIAL MACHINE

As constructed, the compressor is made substantially entirely of seamless steel tubing, gas-welded. No provision is made for opening it in the field, as no occasion is anticipated necessitating any repair within the cylinder.

Fig. 9 shows the parts of a mercury cylinder ready for assembly, including an aluminum radiator.

The mercury compressor, as now being commercially produced, is shown in Fig. 10. It is mounted in an angle-iron frame, and operates at speeds varying from 360 to 440 r.p.m., according to the temperature of the surrounding air.

At these speeds the compressor develops from 35 to 50 lb. pressure, and passes about one and one-third cubic feet of free air per minute. A $^1/_4$-hp. motor supplies the power.

A suitable counterweight is shown, by means of which the unbalanced forces incident to the eccentric position of the mercury cylinder are completely neutralized.

Since the free mercury surface remains substantially constant during operation, the device balances as readily as a simple rotating mass, and shows no tendency to change over the range of operating conditions encountered.

The machine has a forced-feed lubrication system for the bearings, all oil being stored in the pedestal which supports the main vertical shaft. This oil may be withdrawn for renewal by removal of a plug in the base of the pedestal, and such renewal in no way involves the gas circuit of the system.

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As commercial machines are required to be shipped by all types of conveyances, and delivered by motor trucks, express carts, etc., provision had to be made for retaining the mercury within the compressor even though the machine should be tipped on its side or completely inverted. This is accomplished by the use of traps at the outlet ends of the flexible coils. These are so arranged that the mercury will fall back into the cylinder upon righting the machine and turning it slowly in the operating direction.

The motor drive, as utilized in the commercial machines, is a rubber friction wheel running on a cast-iron driven wheel rigidly attached to the rotating frame. For convenience in meeting commercial requirements, and in order to operate the machine more slowly during the cooler portion of the year, provision is made to shift automatically the position of the motor, thereby varying the speed of the machine according to the room temperature. This mechanism has proved to be entirely reliable in service.

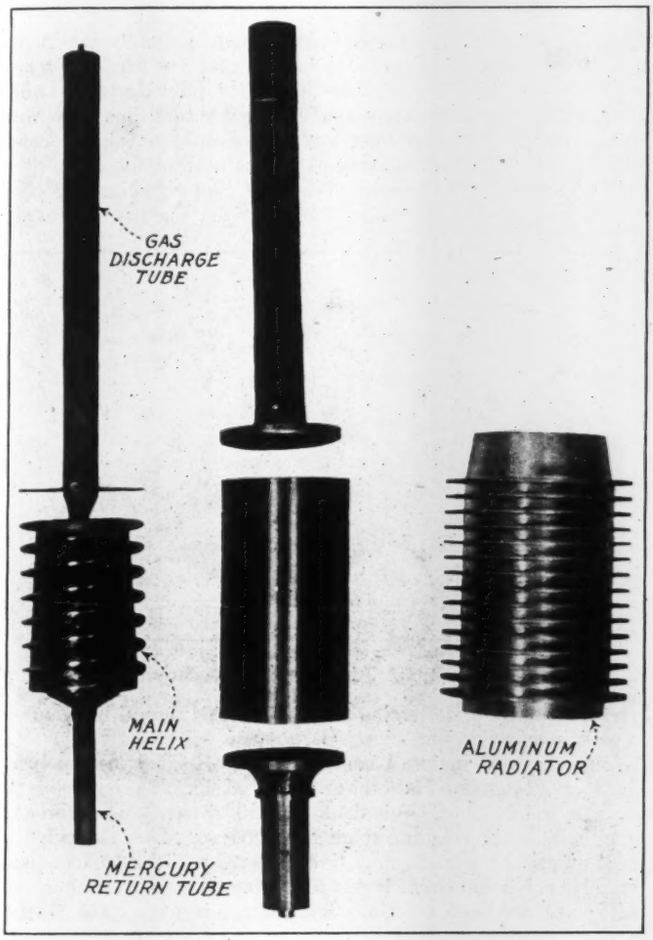

FIG. 9 PARTS OF MERCURY CYLINDER READY FOR ASSEMBLY, SHOWING DOUBLE-THREAD MAIN HELIX, MERCURY RETURN TUBE, GAS DISCHARGE TUBE, AND ALUMINUM RADIATOR

Since the losses in this compressor are limited to mechanical bearing friction, windage, and mercury friction, the resulting efficiency is necessarily very high.

FUTURE POSSIBILITIES

Studies are under way at the present time looking to the application of this compressor on both larger and smaller scales.

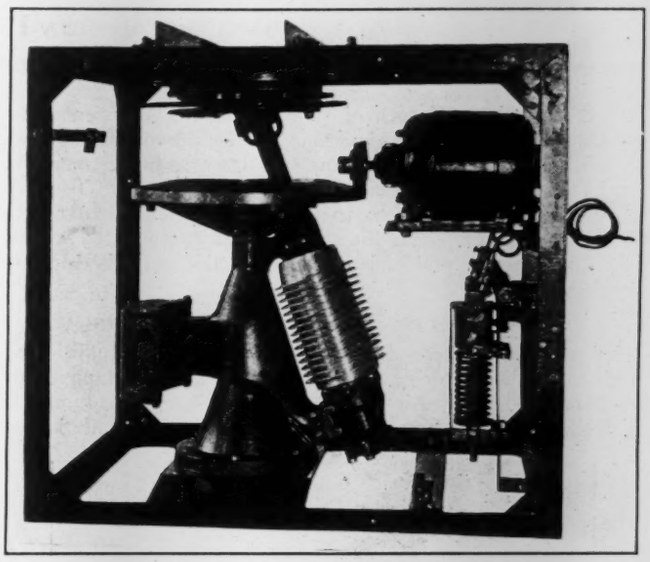

FIG. 10 MERCURY COMPRESSOR SHOWING ROTARY MOUNTING FRAME, FRICTION DRIVE, AND SPEED-VARYING DEVICE

For small-scale applications the rigid-element type of machine, having no internal moving parts whatsoever and being completely sealed shut, is very appealing. These bottle-like elements could be shipped anywhere, and have no possibility of getting out of order once they are properly tested and charged with refrigerating gas and mercury. Small application of the flexible-tube type of machine is also very encouraging owing to the inherent simplicity of the compressor and its quietness of operation.

Larger-scale applications involve consideration of higher-speed operation, as well as novel means of increasing the ratio of gas volumes to mercury quantity, since the mercury cost would necessarily rise in larger-sized units.

In this connection it is interesting to note that the capacity of this compressor in refrigeration terms increases with the cube of the speed, assuming of course that a suitable refrigerant is available to utilize the full pressure developed at any speed selected.

Since there are no lubrication difficulties encountered, the machine will handle any gas which does not react chemically with iron or mercury.

The permanence of operation of the machine having been fully established, there seems to be no inherent obstacle to its use in refrigeration practice of considerable magnitude, and it is probable that other applications of the compressor will also be made. For instance, as a vacuum pump, the degree of vacuum would be limited only by the vapor tension of the mercury.

Development and Construction of the Standard Army Parachute

Description of Standard Army Parachute—Experimental Tests and Results—Difficulties Attending Compilation of Reliable Parachute Data—Important Characteristics of Parachutes—Trend of Modern Parachute Development

By JOHN BONFORTE,[1] DAYTON, OHIO

THE Parachute Branch of the Engineering Division of the United States Army Air Service, under the direction of Guy Ball, Major E. L. Hoffman, and other technical men, has brought the parachute to a high degree of development. The present paper has two aims: first, to discuss the construction, strength, and function of each part of the standard Army parachute; and second, to indicate the problems and experimental methods employed in its development.

Description of Standard Army Parachute

The parachute whose dimensions, strength, and qualities are described in the following pages is the one now in standard use throughout the Army Air Service. It has also been adopted by the United States Navy, The United States Air Mail Service,

Fig. 1 U. S. Army Air Service Standard Seat-Type Parachute and Harness

and several European nations. Fig. 1 shows the parachute in position, illustrating the manner of fastening to wearer and position of rip-cord ring for releasing contents of pack.

The parachute may be subdivided into five parts: the pilot chute, the mainsail or body, the shroud lines, the harness, and the pack. The total weight of the parachute is 18 lb., which is subdivided approximately as follows:

Pilot chute	0.6 lb.
Silk in mainsail	5.0 lb.
Shroud lines	3.5 lb.
Harness	5.0 lb.
Pack	2.0 lb.
Rip cord, vent rubber, and miscellaneous parts	1.9 lb.
Total	18.00 lb.

[1] Aeronautical Engineer, Engineering Division, Army Air Service.

Contributed by the Aeronautic Division for presentation at the Annual Meeting, New York, N. Y., December 6 to 9, 1926, of The American Society of Mechanical Engineers. All papers are subject to revision.

Pilot Parachute. The pilot parachute (Fig. 2), commonly known as the pilot chute, is an octagonal piece of silk (generally considered a disk three feet in diameter) attached to a folding wire frame and double wire spring. The construction of the pilot chute is similar to that of the mainsail, except that its eight shroud lines are continuous through a loop covered with cockscomb serving, by which it is attached to the shroud lines of the mainsail at the apex by a 6-in. line (Fig. 3). The function of the pilot chute is to insure a positive, quick opening of the mainsail by springing open as soon as the

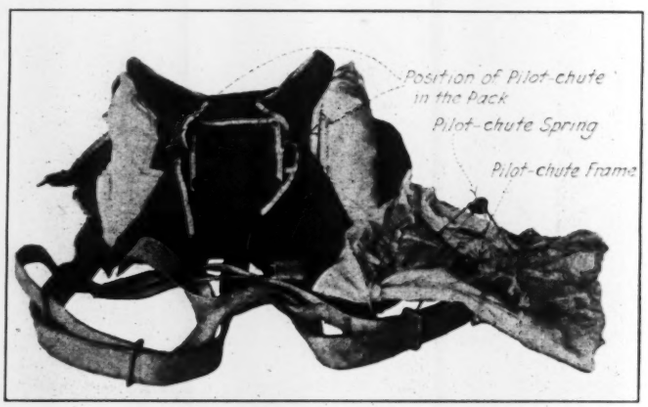

Fig. 2 Appearance of Pack Just Before Insertion of Pilot Chute

rip cord is pulled, and drawing the mainsail and shroud lines out of the pack in an orderly manner.

Mainsail. The mainsail consists of a 24-sided flat polygon (Fig. 4) of 12-momme Habutai or Shanghai silk. (A momme is the Japanese weight unit equivalent to 0.13228 oz. Therefore 12-momme silk is silk weighing about 1.6 oz. per sq. yd.) The polygon, for all practical purposes, may be considered as a disk 24 ft. in diameter. Its polygonal shape is due to the fact that it is easier to construct a polygon than a circle. The polygon is made up of 24 similar trapezoidal panels, each having a base and height of 37 in. and 137 in., respectively, exclusive of fabric necessary for seams.

Each panel is made up of four pieces of silk sewed together on a 45-deg. bias. The division of the panel into four pieces is made to localize a tear, should one occur; while the sewing on the 45-deg. bias is done to obtain the maximum possible strength of the material used. Double stitching is used between sections of a panel, while quadruple stitching is used between panels, and quadruple stitching plus a one-inch reinforcement tape is used around the skirt and around the vent.

Vent. When all the panels are sewed together a polygonal hole, known as a vent, is formed at the center of the mainsail. In this particular parachute the vent is a flexible one. The function of this vent is to relieve the silk fabric of the unusually large load imposed upon it during the time of opening. The load on a parachute may vary from ten times the normal, in an extreme case, down to the normal load consisting of the weight of the aviator plus that of the parachute. Because of this variation in pressure the vent is made variable in size by sewing an 18-in. collar or chimney on the upper edge of the panels. The variation in the size of the vent is obtained by sewing a rubber band through the upper seam of the collar, which then expands or contracts, depending upon the amount of the pressure under the mainsail.

Shroud Lines. Through each of the 24 interpanel seams there is enclosed a shroud line which is attached to the mainsail by a zig-

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zagging machine in four places along the seam. Since the shroud lines are continuous from D-ring to D-ring of the harness (Fig. 3), there are only 12 actual shroud lines used. Each of these lines is $56\frac{1}{2}$ ft. long, 23 ft. being enclosed within the seams of the mainsail, 16 ft. projecting from opposite sides of the mainsail, and $1\frac{1}{2}$ ft. passing freely through the vent. The 16-ft. length of shroud line extending from the skirt of the mainsail to the D-ring is of main interest, as it functions solely as the true shroud line, transmitting the load from the lift webs to the mainsail. The portion of the shroud lines inclosed within the mainsail aids in reinforcing the mainsail and so is really part of it.

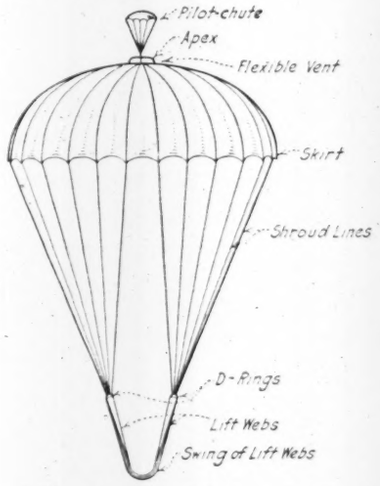

FIG. 3 AN INFLATED PARACHUTE WITHOUT HARNESS

D-Rings. The ends of the shroud lines are tied to four D-rings and the loose ends are then sewed with a zigzagging machine. Six shroud lines taken in consecutive order around the skirt are attached to each D-ring, and each D-ring is fastened to a main lift web (Fig. 3) made of 3-ply linen webbing, approximately $\frac{5}{32}$ in. thick and $1\frac{3}{4}$ in. wide. In Fig. 3 only two lift webs are shown, because each lift web lies flat upon another, to which it is firmly sewed with waxed harness thread. The lift webs are continuous from D-ring to D-ring, so that the swing of the lift webs forms the seat of the harness.

Harness. The harness (Fig. 5) consists of two pieces of webbing which cross at the shoulder blades, rise over either shoulder, fasten across the chest with a breast snap in a D-ring, and then are turned backward to form a waist belt. Two additional pieces of webbing of the same material are attached to the swing of the lift webs with D-rings and snaps to form the leg straps. The function of the harness is to keep the aviator in the swing of the lift webs, so that in no possible position does a direct load fall on any part of the harness.

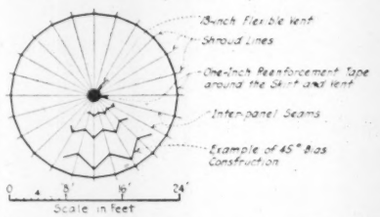

FIG. 4 CONSTRUCTION OF MAINSAIL

Pack. The pack has been studied as long and as carefully as the mainsail itself. As a result, there has been evolved the present type which, in addition to its function as a container, aids the mainsail in opening, prevents the shroud lines from becoming tangled, keeps the mainsail dry, and forms a neat compact bundle. In Fig. 6 may be seen four of the six pack rubbers which draw the sides of the pack open when the rip cord is pulled; this illustration also serves to show the neatness and the compactness of the bundle. Figs. 7 and 8 illustrate how the pack pockets keep the shroud lines from becoming tangled and hold them in place while the pilot chute is drawing the mainsail out of the pack. The pack keeps the mainsail dry, because its fabric is rubberized on the outer surface. (The pack in the illustration is not rubberized.)

STRENGTH OF THE PARACHUTE

As a result of extensive tests it was decided that the largest possible load that would ever be imposed upon a parachute would be about 2500 lb. To allow a safe margin for unknown factors, such as wear and tear, low-grade material, and poor workmanship, a factor of safety of 4 was adopted. Consequently, the present U. S. standard service parachute is built to withstand a breaking load of 10,000 lb.

Beginning at the seat of the parachute, formed by the swing of the lift webs, the strength of each of the various parts is as follows:

Each lift web has a breaking strength of at least 2800 lb., resulting in a minimum total breaking strength of four lift webs of 11,200 lb.

Each D-ring is actually tested with a 2500-lb. load before being used, bringing the total strength of the four D-rings to in excess of 10,000 lb.

Each shroud line has a breaking strength of at least 420 lb., insuring a minimum total breaking strength for the 24 shroud lines of 10,080 lb.

This analysis does not include the strength of the waxed 8-cord linen harness thread attaching the lift webs to the D-rings, nor the strength of the fabric in the mainsail. The strength of the harness stitching is not included, because it is far in excess of the strength of the webbing. The strength of the silk fabric is not included, because the exact facts regarding the manner in which the load is imposed upon the mainsail during the time of opening when the load reaches its maximum are practically impossible to obtain.

FIG. 5 SEAT-TYPE PACK AND HARNESS

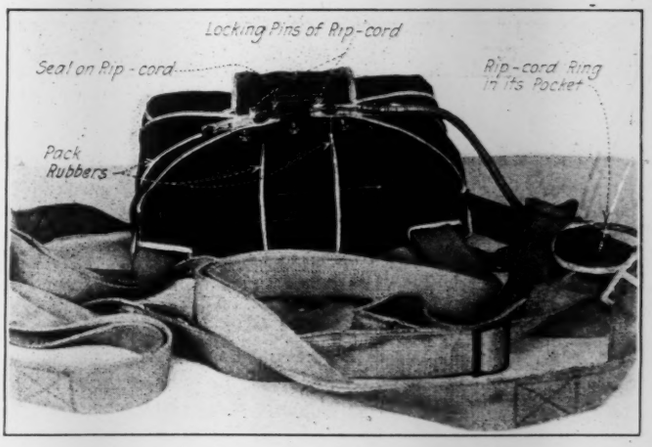

FIG. 6 PARACHUTE COMPLETELY PACKED
(Open flap is a cover for locking pins and cones.)

Fig. 9 shows how the parachute becomes inflated progressively from the apex to the skirt. To determine the load per unit of area at any time during the opening it would be necessary to know the load on the fabric at that time and the area of the fabric under pressure at the same moment.

To determine the load on the fabric at any instant it would be

necessary to know all but one factor in the following equation:

$$Ft = Mv_1 - Mv_2$$

where F = the load on the parachute in lb.
t = time interval in sec. between v_1 and v_2
M = weight of dummy plus chute divided by g
v_1 = maximum velocity of dummy and chute in ft. per sec.
v_2 = velocity of dummy and chute at any time after attainment of v_1 up until the terminal velocity of the parachute is attained.

F at any time is unknown, but t could be measured if a motion-picture camera with a chronographic attachment were used, so that each exposure would photograph the timing device as well as the dummy and parachute. Another possible method of obtaining the time would be by the use of a geared camera whose revolutions per second were known. The value of v_1 may be approximated, but the author knows no way of measuring it directly; v_2 cannot be measured if v_1 cannot.

However, failing to find the unknown factors in this equation directly, one may resort to an indirect method by attaching between

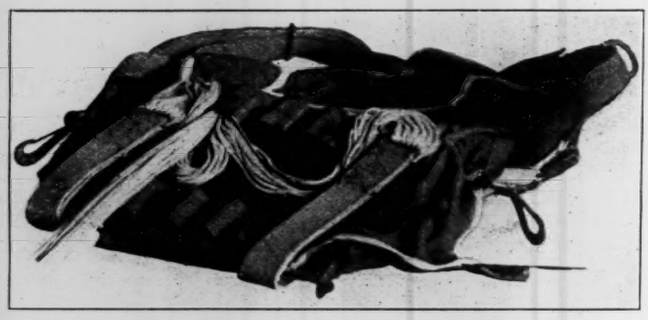

FIG. 7 METHOD OF INSERTING SHROUD LINES IN PACK POCKETS

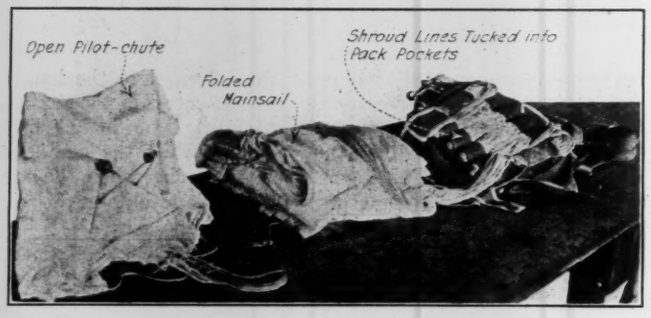

FIG. 8 PARACHUTE IN PROCESS OF PACKING

the lift webs of the parachute and the dummy a dynamometer whose indicator would remain at the maximum reading. Then, by taking v_2 equal to the terminal velocity, a value of v_1 would be found. Since the value of F obtained with the dynamometer would not give the maximum load on the silk per unit of area, it would be necessary to calculate the deceleration of the parachute, and from this new equation find values of F at various times during the opening.

These approximate values of F could be found by this method, but then it would be necessary to know the area of the silk under tension to determine the load per unit area. Reference to Fig. 9 will show the difficulty of obtaining any accurate measurement of the silk fabric under tension during the time of opening. Even if this measurement were obtained and all the other steps in this process also were successfully achieved, one would then have only an approximate value of the maximum load per unit area on the silk fabric for one parachute, with one load, at one speed, performed on one day, under one set of weather conditions, and one combination of the human equation.

In view of the number of variables involved in obtaining the value of the maximum unit load upon the mainsail, it appears doubtful that the time and trouble in finding it are repaid by a knowledge of its value.

It is safe to say that in this parachute the mainsail is the weakest link in the chain, which is as it should be. The reason for this is that, if a break should occur in the lift webs, a D-ring or a number of the shroud lines, it would almost certainly end fatally for the aviator. On the other hand, if a break should occur in the silk fabric of the mainsail, it would likely only increase the rate of descent by a slight amount. As an example of this, it may be stated that during experimental drops of parachutes some descended with a panel ripped from the vent to the skirt with only a moderate increase in velocity.

When a break occurs in the mainsail the pressure under it is relieved so that the rip does not spread. The localization of rips in the silk fabric is also helped by the construction of the mainsail, as has been explained.

EXPERIMENTAL TESTS

Patient trial-and-error experimentation has been the basis upon which the U. S. standard service parachute has been developed. As a result its design is simple in every detail, unencumbered by any complicated mechanical devices.

The airplane used for the experimental tests is a Navy Douglas DT-2, with the fuselage reconstructed so that three dummies can be dropped from it singly or simultaneously. The parachutes are attached to the dummies by the regular service harness. Each dummy is suspended in a compartment separated from the others by vertical panels. The rip cord is attached to a cord fastened to the fuselage. The dummy is released during flight by a lever in the pilot's cockpit.

These experimental tests may be divided under three heads: (1) time-of-opening tests, (2) rate-of-descent tests, and (3) breaking-strength tests. All the tests have been conducted under full flight conditions. Several attempts have been made to utilize the standard N.P.L. wind tunnel at McCook Field, but the tests were so obviously unsuccessful that they were soon discontinued.

The time-of-opening tests are conducted with a 100-lb. dummy at an altitude of about 300 ft. and an air speed of 85 m.p.h. A motion-picture camera photographs the dummy as it leaves the airplane and follows it down to the ground. A chronograph electrically attached to the camera records the time intervals for each complete revolution of the crank of the camera. The exposures average closely around 17 to the second. In Fig. 9 prints have been selected from one of the films obtained by this method showing the progressive steps in a parachute opening. The prints have been arranged to approximate the curve described by the dummy and parachute. The time interval between each print is approximately $^1/_2$ sec.

From this film three things are determined: (1) the interval from the time the dummy leaves the airplane to the time the pilot chute emerges (print 1); (2) the interval from the emergence of the pilot chute to the time the mainsail is out of the pack, (print 2); and (3) the total elapsed time for the mainsail to open completely (print 10).

The method of the opening of a parachute is not a haphazard affair. When the aviator pulls the rip cord, events follow in regular sequence: (1) the locking pins on the pack are released, allowing (2) the pack rubbers to draw the pack open, which allows (3) the pilot chute to spring out and open (Fig. 9, print 1).

The continuation of the progressive steps of a parachute opening may now be followed through the remaining prints. The air resistance of the pilot chute draws the mainsail (print 2) and shroud lines (print 3) out of the pack. As soon as these become taut (print 4), air begins to enter the mainsail at the skirt, traveling upward, and lodging in the apex (print 5). With the continuation of the passage of air into the mainsail, the hemispherical form of the parachute extends gradually from the apex down to the skirt until the mainsail is fully inflated (print 10).

The action of the opening of a parachute described above with the consequent travel of pressure distribution from the apex to the skirt is similar to that which would be obtained by the filling of a canvas bag with water. The last two prints in Fig. 9 illustrate the oscillation of the parachute, which in this case is quite pronounced. The elimination of this oscillation is one of the main problems of the parachute designer.

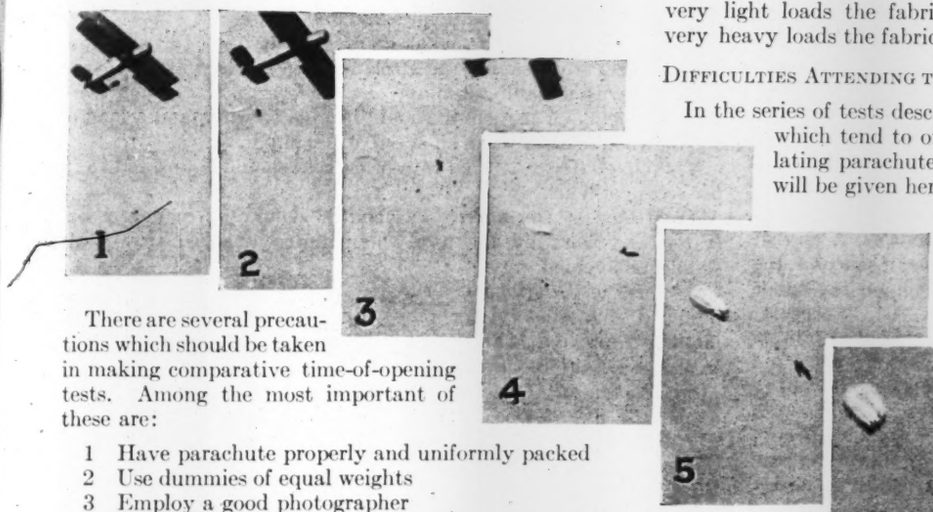

FIG. 9 ILLUSTRATION OF THE OPENING PROCESS OF A PARACHUTE

There are several precautions which should be taken in making comparative time-of-opening tests. Among the most important of these are:

1 Have parachute properly and uniformly packed
2 Use dummies of equal weights
3 Employ a good photographer
4 Have a steady pilot and employ only one throughout the tests.

The pilot's job is to fly at a constant air speed throughout the test, dropping the dummies at an altitude of about 300 ft. The pilot should make proper allowance for sun and wind so that the dummy lands about 100 ft. from the photographer when the photographer's back is toward the sun. The pilot's line of flight should be as nearly as possible perpendicular to a line drawn from the photographer to the place where the dummy is to be released.

The second kind of test given a parachute is the rate-of-descent test. This test depends for its accuracy upon the weather conditions, the pilot, and the timers. It is essential that there be no vertical air currents and preferably no currents at all, vertical or horizontal.

The method of conducting the rate-of-descent test is to release the dummy at an altitude of about 1500 ft., while an observer, on the ground with a stop watch, measures the time of total inflation of the mainsail and the total time of fall of the dummy.

The pilot need not fly at exactly the same speed each time nor at exactly the same altitude for a comparative test, but it is essential that the airplane have no lateral nor longitudinal inclinations at the time the dummy is released.

The third kind of test given a parachute is the breaking-strength test. This test is conducted in the same manner as the rate-of-descent test, except that the dummy is replaced by 100-lb. weights. The weights and parachute are generally released at an altitude of about 1000 ft. and a speed of 100 m.p.h. The weights attached to the parachute are increased in increments of 100 lb. to the breaking load, while the speed is maintained around 100 m.p.h. This method of increasing the load on the mainsail is preferred to that of increasing the speed while maintaining the load constant, because of the difficulty of accurately measuring or calculating speeds of 200 m.p.h. or more.

RESULTS OF TESTS

The results listed below are the observations made during the experimental tests conducted at McCook Field. The parachutes used for these tests were similar to the standard service parachute in every detail except that the fabrics of the mainsail were made of Japanese taffeta silk. The fabrics varied in weight from 0.8 oz. to 2.4 oz. per sq. yd. The porosities of the fabrics varied with the weight, but not proportionately.

1 The variation in porosity of the mainsail apparently makes little difference in the time of opening.

2 The weight attached to a parachute has little appreciable effect upon time of opening.

3 The square of the rate of descent of two parachutes varies inversely as their porosities.

4 The square of the rate of descent of a parachute varies with the load.

5 Statements 3 and 4 lead to a fifth observation, namely: the shape of the mainsail remains the same regardless of the load or the porosity of the fabric, within limits. The limits are the range of loads within which the mainsail will remain inflated. Under very light loads the fabric will assume a saucer-like shape, while under very heavy loads the fabric or the shroud lines will give way.

DIFFICULTIES ATTENDING THE COMPILATION OF RELIABLE PARACHUTE DATA

In the series of tests described above several precautions were mentioned which tend to offset some of the inherent difficulties in accumulating parachute data. A more detailed list of these difficulties will be given here, which will partly explain the present scarcity of reliable parachute data.

1 *Silk.* Under the supervision of Lt. George W. Polk, Mr. Cleary of the Fabric Section of McCook Field tested various specimens of fresh, new silk to determine their porosities under various tensions. He measured the porosity of the various silks under a tension of $^1/_{10}$ in. of water pressure and under increments of $^1/_{10}$ in. up to 1 in. of water pressure. Then he reduced the tension to $^1/_{10}$ in. of water, found the porosity, and in each case noticed that the porosity found the second time was considerably less than that recorded the first time. When the tests were started the silk was fresh, new, and clean; by the time the tests were near completion the silk had absorbed sufficient dirt and moisture to change its qualities. This variation in porosity would affect the resistance of the parachute to a corresponding degree and thus give conflicting results in a rate-of-descent test.

2 *Manufacture and Construction of a Parachute.* During manufacture, a parachute cannot be subjected to rigid measurement. Therefore slight errors of judgment and workmanship creep in which may not impair the functioning of the parachute but will modify its performance.

3 *Packing.* There are numerous small details in the packing, which if not properly attended to, will affect the uniform performance of the parachute.

4 *Position of the Dummy and Parachute as They Leave the Airplane.*

a The dummy may blanket the pilot chute, delaying or preventing it from pulling the mainsail out of the pack.

b The fixed rip-cord puller may get wound around the dummy so that upon leaving the ship the dummy is spinning rapidly. This will cause the dummy to wind and unwind itself around the mainsail; sometimes the dummy does not unwind itself, striking the ground with a tremendous velocity.

5 *Velocity and Attitude of the Airplane.*

6 *Wind.*

7 *Trained Ground Personnel.*

a Photographer
b Timers
c Those attaching parachute to the dummy and the dummy into the test ship.

8 *Difficulty of Finding the Coefficient of Resistance of a Parachute.* The well-known formula

$L = KAV^2$ is applicable to parachutes in determining their velocity or rate of descent, in which

L = weight of pilot plus parachute
K = coefficient of resistance of the parachute
A = projected area of the parachute
V = velocity or rate of descent of the parachute.

The simplicity of this formula is deceiving. The only positive, known factor in it is the load. The rate of descent of a parachute with a given load may be found approximately, if the test is very carefully conducted, but that still leaves two unknowns, K and A.

K depends for its value upon the shape of the mainsail and the porosity of the fabric. A depends for its value upon the shape

Fig. 10 Lap-Pack Parachute

of the mainsail. K and A, therefore, are interdependent. Attempts to measure A from photographs have proved unsuccessful.

The knowledge of the exact values of K and A have more importance academically then practically. Even if one knew the exact weight of the aviator dressed in flying clothes, the exact value for K, and the exact value of A, one could not say that the aviator would strike the ground with a specific velocity, for two reasons:

1 Any air currents present will vary the terminal speed of the parachute. Even a side wind of 10 m.p.h. would increase the force of striking the ground nearly 50 per cent; a vertical air current would add or subtract directly to the terminal speed.

2 Oscillations of the mainsail will cause the aviator to strike the ground with a velocity totally different from the normal. The aviator at the end of the shroud lines may be considered as the ball of a pendulum, and he would only have to be between four and five feet above center to strike the ground about twice as hard as normally.

Important Characteristics of Parachutes

The most important characteristics of a parachute are:

1 *Certainty of Opening.* It is naturally a prime requisite of a parachute that it be fully open in as short a time as possible consistent with safety. A parachute should be so designed that its functioning will be a compromise between the requirements of (1) excessive speed and (2) low altitude. The first calls for a slow-opening parachute, the second for a quick-opening parachute.

There are two phases to the time of opening of a parachute—first, the time required for the mainsail to get out of the pack, and second, the time required for the mainsail to become fully inflated. Under all circumstances the first phase should be as short as possible and the second as long as possible consistent with safety. The reasons are clear and simple. The sooner the mainsail is out of the pack, the sooner will the aviator be suspended in safety; while the longer the mainsail takes to inflate, the less will be the shock of opening on the parachute and man alike.

A fair requirement for a parachute is that it be fully inflated within 4 sec. after leaving the airplane when released at a speed of 85 m.p.h. with a 100-lb. dummy.

2 *Strength.* A parachute should be able to withstand a load of 400 lb. when released at an air speed of 100 m.p.h.

3 *Rate of Descent.* The rate of descent should not exceed 18 ft. per sec. in still air.

4 *Method of Operation.* Parachutes should be manually operated and worn by the user. Parachutes attached to aircraft should be avoided.

5 *Ease of Detachment.* The parachute harness should be so designed that the aviator may disengage himself readily upon landing to prevent his being dragged along the ground or entangled in the parachute in water.

6 *Mechanical Devices.* Mechanical contrivances should be avoided.

7 *Comfort of Wearer.* A parachute should not interfere with the duties of the aviator, nor give him discomfort during his journey through the air. A parachute should also be examined to discover

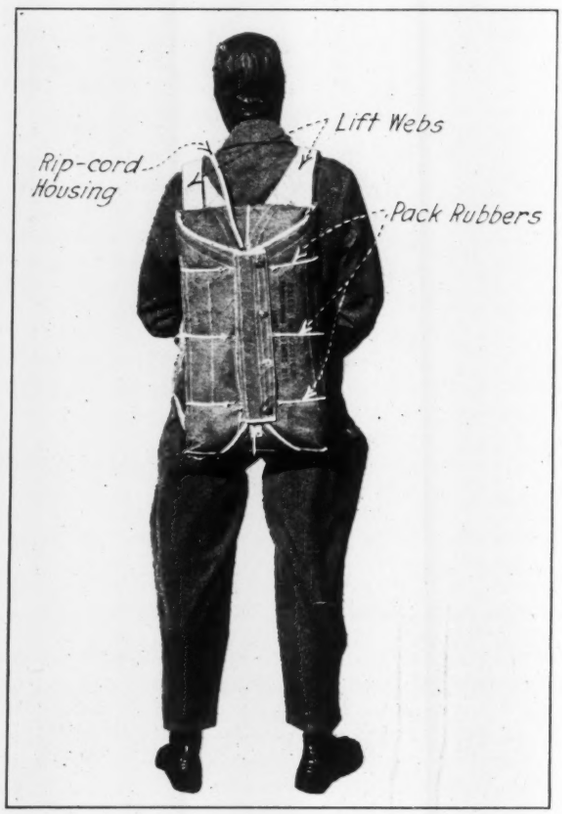

Fig. 11 Back-Type Parachute

where the shock of opening is imposed upon the body of the aviator. The complete parachute should not weigh more than 20 lb., preferably less.

8 *Maintenance.* The packing of the parachute should be comparatively simple, and the time of packing should not be above 20 min. for two men. Replacement of parts should not be excessive.

The Trend of Modern Development

There are two distinct trends to present-day parachute development, one being toward the employment of a domestic fabric to replace the foreign silk used in the mainsail, and the other toward the adaptation of the present service parachute to all branches of aviation.

The search for a domestic substitute with qualities as good as those of silk will probably prove difficult, for no other known fabric possesses the following qualities of silk, even closely: (1) strength-

weight ratio, (2) compactness, (3) elasticity, (4) springiness,[2] and (5) quality of slow combustion. The search, however, will uncover good and reliable substitutes that may be used in time of a national emergency.

The adaptation of the present service parachute to all branches of aviation divides itself naturally into two parts: viz., military uses and commercial uses. The military uses can be further subdivided into those for heavier-than-air craft and those for lighter-than-air craft.

In heavier-than-air craft it is believed that the present seat pack is the most suitable for pilots, and passengers with whom mobility is not essential. However, for photographers, gunners, and others similarly employed, a new type of pack and harness will have to be developed. The present type has proved too inconvenient and liable to accidental opening, due to parts of the pack hooking on to some projecting object in the airplane.

Experiments have been tried with a lap pack (Fig. 10) and a back pack (Fig. 11), but neither has shown any marked advantage over the seat pack in the allowance of greater freedom of movement or the prevention of accidental opening. Consideration has been given to packing a parachute in a flying suit with the harness built directly into the suit. The objections to this combination flying suit and parachute are the difficulty of packing, the necessity of making each suit tailor-made for each aviator, the consequent high cost, and objections from a production viewpoint. However, it appears that the equipment of those requiring mobility will have to include some type of combination of flying suit and parachute.

In lighter-than-air work it is believed that the present seat pack is suitable for the aeronaut in balloons, as he is not required to move about extensively.

In airships, parachutes present a wholly different problem than in either the balloon or the airplane. In airships there are men who must perform a wide range of duties and, therefore, require facility of movement; some are in the control car, some are in the power cars and some must travel up and down ladders and on narrow "cat walks."

For those whose movements are limited to just one car the lap pack should prove the most suitable, because in an emergency their movements would not be seriously impeded, and the pack would be before them where they could prevent its becoming caught in any projecting object. It may be that the personnel in airships need not wear their parachutes continuously during flight, as the record of accidents to airships thus far seems to show that the crew has plenty of forewarning of impending danger.

For those members of the crew of a large airship whose duties take them to various parts of the ship, it would seem a feasible plan to place parachutes in various parts of the ship in much the same manner that life preservers are placed in advantageous positions on a sea-going vessel. Should it occur that only one parachute was available for two men, it is possible that one man could wear the harness and the other man could cling to him. This would increase the rate of descent appreciably, but it would still be sufficiently low to save their lives.

For commercial aviation the same parachutes worn by army personnel could be worn by civilian personnel performing similar duties. For passengers in commercial aircraft the present seat-type pack should prove suitable with a few slight changes. The pack, covered with a kapok cushion, could serve as a seat for the passenger, while the harness could be hung on the back of the seat, so that the passenger's arms could slip into it readily when necessary. Women passengers, it seems, will have to change their style of dress or incur added danger in case of emergency. Suspension of the body from the waist or the armpits is possible, but not desirable.

In conclusion, it may be said that the passenger in an aircraft who has a parachute available should feel safer than in any other transport vehicle in existence. Accidents on railroads and in automobiles or steamships generally come without warning and often end fatally. An accident to an aircraft still gives the passenger a second chance for life via the parachute. To date thirty men owe their lives to parachutes, and three of these owe a double debt.

[2] By springiness is meant that quality of silk which causes it to spread outward when released from the confinement of a pack.

The Fusion-Joining of Metallic Materials in Aircraft Construction

By SAMUEL DANIELS,[1] DAYTON, OHIO

The joining of metallic materials by fusion processes is common practice in aircraft construction, welding, brazing, and soldering all being frequently utilized. Welding is primarily resorted to where the joints form part of the main airplane structure. The author describes the technical methods of welding fully, and points out that oxyacetylene welding has successfully passed the experimental stage, while electric-arc welding has not reached anything like the same degree of development. Gas welding, particularly in fuselage construction, has been applied not only to plain-carbon tubing, but to alloy-steel tubing likewise, particularly chrome-molybdenum. With plain carbon the strength of the joint is only 80 per cent of that of the raw material, but the air-hardening property of chrome-molybdenum steel allows the full strength of the material to be developed. Special care has to be given to joints exposed to shock or fatigue. Specifications and methods for welding aluminum and aluminum alloys are given in the paper. Brazing is mainly employed in connection with the manufacture of fittings and is not relied upon for structural connections, while soldering is only used for such parts as gasoline lines and wrapped terminals. The paper is particularly valuable because it assembles for the first time, in a seasoned manner, the considerable amount of information now available on these three processes as applied to aircraft construction.

METALLIC materials may be joined either mechanically, as by riveting, bolting, keying, or pressing, or through fusion processes, exemplified by the operations of welding, brazing, and soldering, which will be considered at length because they are metallurgical in character. The term "welding" postulates the application of sufficient heat to carry the material to a plastic or to a molten state and embraces forge welding, arc welding, gas welding, resistance welding, and thermit welding. Brazing is the method of joining through the alloyable medium of non-ferrous alloy of copper base, reduced to a molten condition between the parts to be joined, whose melting point must be higher than that of the brazing material. Soldering is similar in nature to brazing, with the exceptions that the soldering material is generally of comparatively low melting point and that usually, omitting the case of some hard solders, it forms no alloy with the parts to be soldered. Soft-soldering involves the use of the solders of tin-lead or of tin-zinc base; whereas hard-soldering connotes the use of a soldering stick of melting point much in excess of that of the tin-lead solders, as illustrated by the silver (silver-copper-zinc) solders.

Welding in Aircraft Construction

Arc and gas welding and, to less extent, resistance welding, are employed in airplane manufacture, more particularly with reference to steel.

Arc Welding. Electric arc welding is still in the experimental stage as far as fuselage construction is concerned, and it remains to be seen whether this process will reach the efficiency of gas welding. In arc welding either direct or alternating current may be used.

The electrode may be either carbon or metallic. With the carbon electrode and (preferably) direct current, the arc is from the work, which is the positive pole, to the carbon, which is the negative, and the filler stick is simply fused into the joint. This type of welding has not been much used in aircraft construction. For the metallic electrode direct-current processes have been more extensively developed, and in them the work is generally the positive electrode, since it has a greater thermal capacity than the negative electrode and accordingly permits more complete fusion. The polarity of the electrode changes every cycle with alternating current. The carbon-metal arc has a temperature of about 7000 deg. fahr. and the metal arc one of about 6000 deg. fahr. The arc of the former is much longer than that of the latter. The requirements for metallic electrodes and for filler stick are outlined in later paragraphs.

The other advantages and disadvantages of arc welding concern operation and flexibility. The type of skill required by the electric welder of aircraft is probably of higher grade than that called for in gas welding, because of the danger of damaging the thin sections. On the other hand, it is apparently more simple to weld in deep corners or sharp angles with the arc weld than with the torch. It is undoubtedly much easier to engage experienced gas welders than electric welders, so that the latter type of personnel may have to be trained on the job. With electric welding, the burden of sources of supply of oxygen and acetylene gas is removed, which might be an advantage in certain phases of large-scale production. The greater mobility of a portable, light-weight oxyacetylene outfit in making repairs upon disabled planes in inaccessible places is, however, unquestioned.

Gas Welding. Gas welding employs the heat of a flame formed by burning a mixture of oxygen and acetylene, oxygen and hydrogen, or air and hydrogen. The weld is made either by fusing the edges of the parts to be joined or by fusing simultaneously the edges and a welding wire or rod. The former method is used principally with aluminum and its alloys and the latter with steel and other alloys of high melting point.

Resistance Welding. In electric resistance welding a single-phase alternating-current circuit is used in which the cleaned pieces to be joined, held between copper dies, form part of a low-voltage, high-amperage line. The points of contact of the two pieces offer more resistance to the passage of current than any other points in the circuit and so the junctions become heated rapidly from their interior outward. Having arrived at the plastic stage, the ends of the steel pieces are brought together under pressure to form a "butt" weld. In "spot" welding, pieces are tacked over small areas, usually for temporary purposes, by fusing the steel pieces at the point desired and by applying pressure to force the molten areas together.

Welding Wire. Filler rod or welding wire should be carefully selected with regard to the type of material to be welded. As a general rule the chemical analysis of the welding rod should be the same as that of the parts to be welded. The Air Service requirements for ferrous and non-ferrous welding wire are given in Tables 1 and 4.

The chemical composition and the physical characteristics of ferrous welding wire are important. The compositions used for steel welds in aircraft construction are given in Table 1.

TABLE 1 AIR SERVICE REQUIREMENTS FOR FERROUS WELDING WIRE

		Chemical Composition, Per cent				
Material	Type of welding	Carbon	Manganese	Sulphur Max.	Phosphorus Max.	Silicon Max.
A	Arc	0.06 (Max.)	0.15 (Max.)	0.040	0.040	0.08
B	Arc	0.10–0.18	0.40–0.60	0.040	0.040	0.06
E	Gas	0.06 (Max.)	0.15 (Max.)	0.040	0.040	0.08
F	Gas	0.10–0.18	0.40–0.60	0.040	0.040	0.06

The wire for electric welding is of "bright hard" or "bright soft" finish and that for acetylene welding is a soft annealed wire. When no welding wire is available, strips of the material to be joined may be substituted with good results, especially in gas welding. Metallic electrodes should be uniform in structure and free from hard spots. A lime wash (flux) is used for coating electrode wires, but fluxes are generally not employed in acetylene welding.

There are several grades of commercial alloy-steel welding wire, but practically all welding done on airplanes has been with the wires described above, which are satisfactory for structural steels not heat treated. Alloy steels, as a rule, are not so easily welded as the plain-carbon, and they are more readily handled when comparatively poor in both alloy and carbon content.

[1] Chief, Metals Branch, Material Section, Engineering Division, Air Service.

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MECHANICAL PROPERTIES OF STEELS WELDED

For fuselage structures the Air Service is using two varieties of seamless tubing—plain carbon and chrome-molybdenum. The plain carbon tubing is 1025 steel, covered by Air Service Specification 10,225-D. This material is free from the variations in yield point and in modulus of elasticity in tension peculiar to 1020 mechanical tubing, which it supersedes. In the matter of alloy-steel tubing for parts which are highly stressed or for short struts requiring high yield point and strength, chrome-molybdenum steel, containing from 0.25 to 0.35 per cent of carbon, 0.40 to 0.60 per cent of manganese, 0.80 to 1.10 per cent of chromium, and from 0.15 to 0.25 per cent of molybdenum, and having minima of 95,000 lb. per sq. in. in ultimate strength and of 60,000 lb. per sq. in. in yield point, is being used successfully in the forward part of the fuselage, in the wing structures, and in the landing chassis. This type of

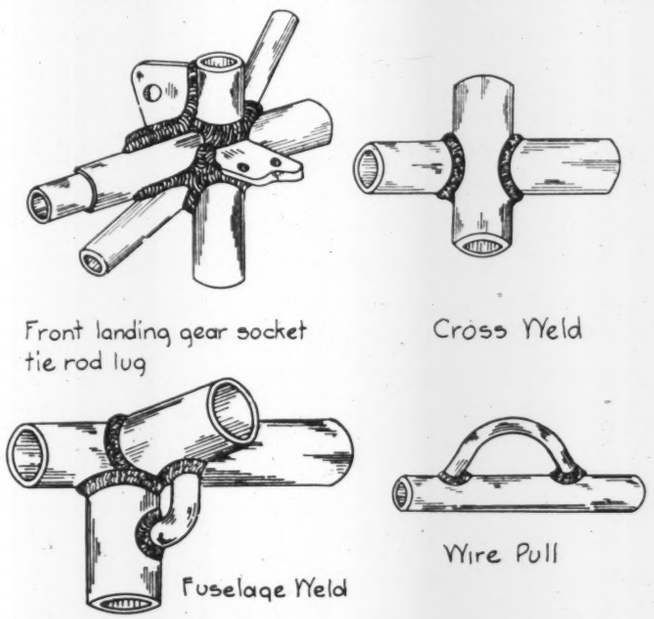

FIG. 1 TYPICAL STEEL WELDS IN AIRCRAFT CONSTRUCTION

alloy tubing, the only one available to definite chemical and physical requirements, is replacing nickel-steel tubing, which not only forms less desirably and which may crack during welding, but also, like chrome-vanadium steel, cannot be drawn to as large diameters and thin walls, essential to the obtaining of the large moment of inertia demanded by the compression loads. Tubing of wall thickness as low as 0.035 in. is used for fuselage and main structural members, but in less important parts, such as tail surfaces, the minimum may be 0.022 in.

For sheet-metal fittings the Air Service utilizes plain-carbon and chrome-vanadium sheet, which are described in Specifications 10,201-D and 10,206-D, respectively. The quarter-hard mild-carbon (1025) steel goes into all fittings and parts so moderately stressed that a heat-treated material is not necessary. For more highly stressed parts which are used only in the heat-treated condition, with heat treatment following fabrication, hot-rolled and annealed 6123 or 6130 steel is the elect among the alloy steels because, in addition to its satisfactory welding qualities, it will withstand severe bending operations (180 deg. over a radius equal to the thickness, without cracking). The carbon-steel sheet is required to have minima of 55,000 lb. per sq. in. in ultimate strength, 36,000 lb. per sq. in. in yield point, and 22 per cent (in 2 in.) in elongation, both parallel and normal to the direction of final rolling. The general requirements for tube, sheet, and strip are listed in Table 2.

TABLE 2 AIR SERVICE REQUIREMENTS FOR RAW STEEL TUBING SHEET, AND STRIP

Material	Mild carbon-steel tubing	Chrome-molybdenum steel tubing	Mild carbon-steel strip	Chrome-vanadium-steel sheet or strip
Air Service Spec. No.	10,225-D	10,231-A	10,201-D	10,206-D
Condition	Normalized	Normalized	Annealed	Normalized or annealed
Chemical Composition:				
Carbon	0.20–0.30	0.25–0.35	0.20–0.30	0.25–0.35
Manganese	0.50–0.80	0.40–0.60	0.50–0.80	0.50–0.80
Sulphur	0.050 max.	0.045 max.	0.050 max.	0.040 max.
Phosphorus	0.045 max.	0.040 max.	0.045 max.	0.040 max.
Chromium		0.80–1.10		0.80–1.10
Vanadium				0.15 Min.
Molybdenum		0.15–0.25		
Tensile Properties:				
Ult. str., lb. per sq. in.	55,000 min.	95,000 min.	55,000 min.	125,000(a) min.
Yield pt., lb. per sq. in.	36,000 min.	60,000 min.	36,000 min.	100,000 min.
Elong. in 2 in., per cent	22 min.		22 min.	
Stock 0.25 in. plus				10 min.
Stock under 0.25 in.				5 min.
Crushing Test	25 per cent increase in O.D.			
Bend Test			180 deg. on radius = T	180 deg. on radius = T

(a) Not required, but material should develop these tensile properties after heat treatment.

WELDABILITY OF STEELS

Investigations by the Material Section at McCook Field[2] have shown that, in the welding of tubing and sheet, mild-carbon, chrome-molybdenum, and chrome-vanadium steels weld satisfactorily. Chrome-molybdenum tubing is readily welded with low-carbon-steel welding wire; and chrome-vanadium lugs are easily bonded to chrome-molybdenum tubing, also with low-carbon-steel wire. The use of a chrome-molybdenum welding wire such as is indicated in Table 3 is attended with more difficulty than is the case when low-carbon wire is employed. The former flows less easily and uniformly. In welding chrome-molybdenum to chrome-vanadium sheet, this alloy wire produces a finer-grained and more uniform structure than the plain-carbon wire. In alloy-steel welds the use of chrome-molybdenum wire may be justified if the assembly is to be heat-treated to exceed an ultimate strength of 100,000 lb. per sq. in. Chrome-molybdenum steel is welded successfully either by the oxyacetylene or the metallic-arc method. Nickel-steel welding wire has given good results in chrome-molybdenum tube welds.

TABLE 3 COMPARISON OF WELDS IN CHROME-MOLYBDENUM AND IN CARBON-STEEL TUBING

	Chemical Composition				Mechanical Properties			
	Carbon	Manganese	Chromium	Molybdenum	Ultimate strength, lb. per sq. in.	Yield point, lb. per sq. in.	Elongation in 2 in., per cent	Location of fracture
Alloy tube	0.32	0.56	0.93	0.23	100,000	70,000	12	.....
Alloy wire	0.28	0.01	1.14	0.95				
Alloy tube and wire, welded					100,000	70,000	4	½ in. from weld
Carbon tube	0.18	0.49			55,000	30,000	20	.....
Carbon wire	0.03	0.48						
Carbon tube and wire, welded					49,000	23,000	47	3 in. from weld

The weldability (and brazability) of chrome-molybdenum to chrome-vanadium parts is important in that the assembly may be heat-treated as a unit without overheating, because the quenching temperature for both is about 1625 deg. fahr. The presence of nickel steel in this hybrid type of assembly is perhaps not dangerous, but it is not to be recommended, at least for highly stressed parts. Overheating 2320 nickel steel by not less than 100 deg. fahr. above the proper quenching temperature coarsens the grain somewhat and probably lowers the fatigue resistance, but the Izod impact resistance is not seriously impaired.[3] Chrome-molybdenum tubing is superior to nickel steel in welding qualities and in strength, raw and heat-treated.

PROPERTIES OF WELDED STEEL JOINTS

The microstructure and mechanical properties of a welded joint, types of which are shown in Fig. 1, depend not only upon the nature of the materials and upon that of the welding stick, but also upon the welding process and its method of application. Heat treatment after welding further influences the characteristics of the joint.

Microstructure. The fused portion of the steel joint has, of course, the large grain typical of a casting. The steel adjacent to the focus of the weld is also coarse grained, because of the high temperature to which it is subjected; but as the distance from the focus increases the grain size becomes smaller and smaller, until it attains that very

[2] Sisco and Boulton, Welding Steel Tubing and Sheet with Chrome-Molybdenum Welding Wire, Trans. A.S.S.T., Nov., 1925.

[3] Sisco, Impact Values of a Nickel Steel, *The Iron Age*, vol. 116 (1925), p. 1513.

fine grain size impressed by a temperature equivalent to that of annealing just above the critical range. Still further from the weld and usually within a short space interval, the structure passes through a spheroidized zone into that of the original material unaffected by the heat of welding. Figs. 2, 3, and 4 show the transitional zones in a chrome-molybdenum tube joint welded with low-carbon welding wire. Fig. 2 is of the alloy tube and carbon wire boundary. The chrome-molybdenum tube has a coarse sorbitic structure, with free ferrite. The metallograph does not, however, illustrate the maximum grain size (attained by the alloy steel in this weld), which was several times larger than the biggest grain shown. Beyond the weld the grain size becomes smaller and the structure passes through the two sharp transitional zones (Figs. 3 and 4) before assuming that of the original tubing, as received, which closely resembles that at the right in Fig. 4. In this particular joint the change from weld to original tube structure occurred within a space of $^5/_8$ in.

Heat treatment of welds refines the grain and alters the structure, thereby improving the mechanical properties. Normalizing and annealing tend to produce a uniform pearlitic or possibly sorbitic structure (with free ferrite) in the weld, with resultant improvement in ductility. Quenching and drawing combine to give at

FIG. 2 JUNCTION OF CHROME-MOLYBDENUM TUBE (BELOW) AND LOW-CARBON WELDING WIRE (ABOVE) JUST OUTSIDE OF WELD FOCUS (MAGNIFICATION × 100)

least the properties conferred by normalizing or annealing, and, with suitable carbon and alloy content, the strength and ductility may be varied through a range prescribed by structures intermediate between martensite and sorbite. Unfortunately, properly controlled heat treatment cannot often be accorded to welded aircraft parts.

Mechanical Properties. The ductility and the impact resistance are not so high in a casting as in wrought material. Therefore a welded joint which is no stronger than the fused portion is not so strong as the original, unwelded stock when subjected to bending stresses and to shock. A cast steel, however, has nearly the same strength as an annealed wrought steel of the same composition and, consequently, in simple tension loading, the welded joint has an efficiency of 100 per cent. The efficiency is less if the wrought material is originally in the cold-worked or in the quenched and drawn rather than in the annealed condition.

The influence of welding is felt in several other ways. The resistance of a welded joint to bending stresses, applied either statically or in a number of cycles, is less than that of the unwelded material. With 1025 tubing the endurance limit (on a rotating beam machine) of gas- or arc-welded joints is about 14,000 lb. per sq. in., some 23 per cent of the ultimate strength of the joint itself. The strength of the joint is close to that of the unwelded tubing and the elongation in 2 in. for both was found, in one investigation, to be approximately 12 per cent (for torch welding). A butt-welded joint in this mild carbon steel will fail when given a transverse bend of about 90 deg., whereas the unwelded sheet will bend 180 deg. Acetylene butt-welded chrome-vanadium (6123) sheet (0.035 in. thick) gave an ultimate strength of about 70,000 lb. per sq. in., a yield point of about 50,000 lb. per sq. in., an elongation of 20 per cent in 2 in., and an endurance limit of from 16,000 to 18,000 lb. per sq. in. No data are yet available on the endurance limit of chrome-molybdenum welds.

In tension tests welded butt joints generally fail outside of the

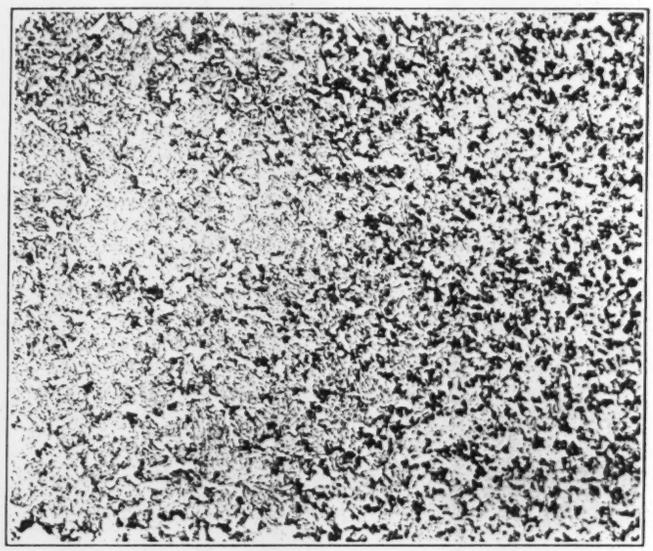

FIG. 3 TRANSITION ZONE IN CHROME-MOLYBDENUM TUBE ABOUT $^1/_4$ IN. FROM SPOT SHOWN IN FIG. 2. NOTE HOW GRAIN SIZE HAS DECREASED (MAGNIFICATION × 100)

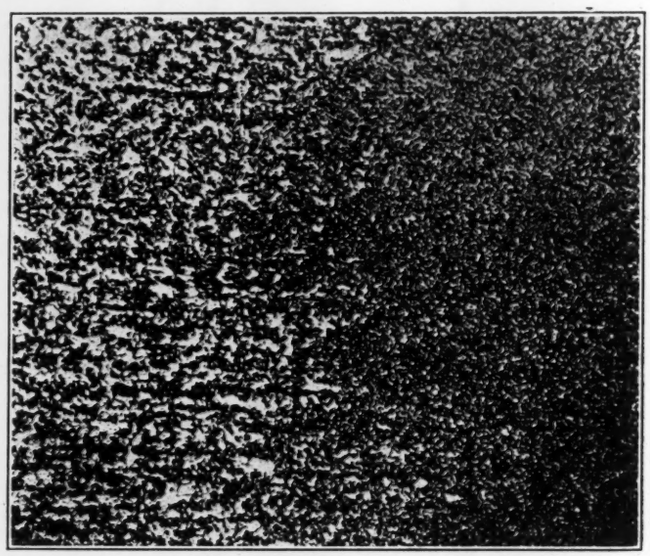

FIG. 4 SECOND SHARP TRANSITION ZONE IN CHROME-MOLYBDENUM TUBE ABOUT $^1/_2$ IN. FROM SPOT SHOWN IN FIG. 2. FINE-GRAINED STRUCTURE AT RIGHT RESEMBLES CLOSELY THAT OF THE ORIGINAL TUBE (MAGNIFICATION × 100)

weld. Failures in low-carbon tubing have occurred under loads as low as 40,000 lb. per sq. in. in locations from $^1/_4$ to $^1/_2$ in. away from the weld. In mild (1025) steel, which welded is stronger, the breaks were considerably removed from the weld focus. In chrome-vanadium sheet and in chrome-molybdenum tubing, the fracture eventuates at a point between $^1/_2$ and 1 in. from the weld. The rupture lies in a zone which is shown by Rockwell hardness tests to be soft. Of course, the greater cross-sectional area at the weld is a factor in throwing the break away from the weld. After heat treatment the fractures still occur outside of the weld, but in no well-prescribed location.

Under conditions of repetitive stress, however, the failure of butt welds has been shown by R. R. Moore[4] to take place in or extremely close to the weld. Fractures in the torch welds were directly through the weld, while in the arc welds they were at the immediate edge of the weld, as in static testing.

Table 3 indicates the comparative strength and ductility of welded and unwelded specimens of chrome-molybdenum and of carbon-steel tubing 1 in. in outside diameter and 0.035 in. in wall thickness. The welds were of the butt type, and the values are characteristic either of oxyacetylene- or arc-welded joints. The air-hardening property of chrome-molybdenum steel causes it to develop in a welded joint 100 per cent of the tensile strength of the unwelded tubing, whereas the carbon-steel weld can be depended upon to the considerable, though inferior, extent of a minimum of 80 per cent of the strength of the raw tubing.

Welds in this chrome-molybdenum tubing, quenched from 1625 deg. fahr. in water, on being drawn at from 800 to 1250 deg. fahr., have given a range of from 155,000 to 110,000 lb. per sq. in. in ultimate strength and from 4 to 17 per cent in elongation in 2 in. Heat-treated chrome-molybdenum welds, especially with chrome-molybdenum welding wire, present interesting possibilities.

Inspection of Welded Joints

The proper inspection of a welded joint is hardly possible without destruction of the weld. In order to determine the extent of the fusion, the cleanliness, soundness, and the structure, it is almost imperative to examine the weld metallographically. The degree of bond, the presence of slag inclusions and of voids, and the nature of the structure may then be exposed. Something, however, may be judged about adherence from chiseling the edges of deposited layers. Bad welds may be revealed by testing the joint with gasoline or slushing compound under pressure, when leakage will appear on the opposite side. Attempts are being made to examine fuselage welds by X-rays.

It is quite feasible, nevertheless, to follow the welding in process. A good weld depends to a great extent upon the experience of the welder. In general, a good weld looks well, shows an even distribution of welding material, and is free from sponginess and scale. Even so, too much reliance cannot be placed upon surface indications. Residual stresses from welding may be largely minimized by proper allowance for the expansion and contraction of the steel.

There are a number of cases where welding is not permissible. Such parts as cables, streamline wire, certain tubular members whose use is governed by their cold-worked strength, and such heat-treated parts as turnbuckle shanks, axles, and upset-headed bolts which owe their properties to a quenching and drawing operation should not be welded. Brazed or soldered parts are subject to the same interdiction, for both brass and solder penetrate hot steel and embrittle it.

Instructions to Airplane Designers on Welding

The clauses below have been taken from the Handbook of Instructions for Airplane Designers, issued by the Engineering Division, Air Service, U.S.A.

Welds are considered to be more reliable under direct compression and shear due to bending than under direct tension, tension due to bending, or shear due to torsion.

Welding of parts in the surface control system and welding under tension in any part whose failure would probably wreck the airplane will not be permitted without the written approval of the Engineering Division.

The unit stresses in welded joints not heat-treated after welding must not exceed 80 per cent of the physical properties of the material in its cold-worked condition. The unit stresses in joints heat-treated after welding may be equal to the physical properties of the material in its heat-treated condition.

No splices shall be made in main structural members (that is, longerons, spars, interplane struts, and landing-gear struts) by butt welds subject to direct tension or bending stresses, unless the joint is reinforced by riveting, pinning, telescoping, or other auxiliary means. Where "fish-tail" welded joints are used on tubes, the angle between the weld and the axis of the tube shall be not more than 30 deg.

The following precautions shall be taken in the fabrication of welded fittings. Welded joints shall not be cleaned up by filing, as such treatment involves serious loss of joint efficiency. Welded joints shall not be filled with solder, brazing metal, or any other filler.

[4] Fatigue of Welds, MECHANICAL ENGINEERING, vol. 47, no. 10, Oct., 1925, p. 794.

Heat treatment to refine the grain structure of a welded joint is not mandatory but is recommended. This can be accomplished by soaking at a temperature corresponding to the quenching temperature and cooling in air.

Welding of Aluminum and Its Alloys

The welding of aluminum-base materials in aircraft construction is employed to a minor extent only. Joints in highly stressed parts are out of the question. The weld, of course, has only the properties of the cast material, and it has not been found possible to improve the strength of the weld by heat treatment, as with steel. The use of the strong wrought aluminum alloys of the duralumin type in fuselage and wing structures, and to less though increasing extent in the landing gear, is dependent upon riveting or pinning (with sheet stiffeners).

Aluminum and its alloys can be welded by any of the methods previously described. These light materials have a low melting point, are hot-short, and are easily oxidized; therefore modifications of the apparatus and more skill on the part of the operator are required to obtain a weld of good workmanship. The welding wire for pure aluminum is a 99 per cent pure, soft-annealed aluminum wire. The welding rod for castings is covered by specification as follows:

TABLE 4 AIR SERVICE REQUIREMENTS FOR ALUMINUM-ALLOY WELDING ROD

	Chemical Composition			
Material	Aluminum	Copper	Iron	Other impurities
Welding rod	91.0–93.0	7.0–9.0	1.50 (Max.)	1.0 (Max.)

Aluminum Castings. The welding of castings is generally done by means of the oxyacetylene torch. The parts are preheated to about 500 deg. fahr. and the welding rod is melted and puddled into the cavities or seams, which have been previously prepared by cutting the edges at an angle of about 45 deg. If there is much welding on a casting it should be annealed after welding. The requirements to be observed in welding of aluminum-alloy castings follow:

Castings shall not be repaired, plugged, or welded without permission from the inspector. Such permission will be given only when the defects are small and do not adversely affect the strength, use, or machinability of the castings. No welding will be permitted on castings which are heat-treated (such as those of 5 copper-1 silicon, the 4 copper-2 nickel-1.5 magnesium, and of the 10 copper-1.25 iron-0.25 magnesium alloys).

Each welded repair shall be encircled with a ring of white paint prior to submission for inspection or shipment.

Aluminum Sheet. The welding of aluminum sheet (as in gas tanks) may be accomplished either by the butt or the flange method. The latter is preferable, however, as it produces a fillet on the underside of the weld; whereas the butt is likely to leave a sharp re-entrant angle which tends to cause failure under vibratory stresses.

In the flange method, the edges to be joined are bent up or flanged an amount equal to about three times the thickness of the sheet. The edges of the sheet are then held together by small clamps and tack-welded at intervals of about one inch by melting the metal together at these points and touching up the joint, if necessary, with a welding stick made from strips of the original sheet. After the clamps are removed flux is applied to both sides of the joint and the weld is completed by melting down the flanges, the operator holding the torch at an angle of 45 deg. with the work and in line with the weld and progressing continually at a uniform speed. Little or no metal is added from the welding strip. A sound and smooth bead should be formed, well rounded on both the upper and lower surfaces.

If there is considerable oxide or heavy film on the sheet, the edges should be cleaned, prior to flanging, by immersion for 10 to 30 sec. in a hot solution of 10 per cent caustic soda or 10 per cent trisodium phosphate. The edges should then be rinsed in a dilute 10 per cent nitric acid solution, and then in hot water, to remove all traces of corrosive flux. The immersion should not be for longer than is necessary to clean the surfaces. If the aluminum sheet is fairly clean, a wire brush or steel wool may supplant the cleaner. Welding fluxes, containing alkali chlorides, sulphates, fluorides, etc., are not always necessary if the surfaces are clean. These mixtures are mixed to a thin paste with water, preferably distilled, and applied with a swab or brush to the welding rod and surfaces to be welded. If the metal is heated slightly the flux will adhere and dry quickly.

All traces of flux must be removed promptly after welding, otherwise corrosion will set in. The flux can be removed by means of a scrubbing brush and hot water, followed by rinsing in running water or by treatment with a dilute 10 per cent solution of either sulphuric or nitric acid, after which the acid is removed by rinsing in cold water.

Duralumin Sheet. The welding of duralumin sheet embodies most of the principles applied in the welding of aluminum sheet and, in addition, is much more difficult to perform. Not only is the cast material in the weld brittle and not susceptible to modification of the cast structure through heat treatment, but duralumin melts, cracks, and warps more easily than aluminum sheet.

Duralumin welds are used, however, in the construction of fuel tanks, fittings, etc., of simple design, where the stresses are not high, and provided that the entire part may be heat-treated after welding and in order to prevent corrosion just outside of the seam. A small oxyacetylene torch is used. Welding across the grain is more difficult than welding with the grain. The welding wire, of the same composition as the material to be joined, and the pieces to be joined are cleaned before welding in the manner described for the handling of aluminum. The fluxes used are the same as those for aluminum and must be removed after welding. Where bends in flanging are to run parallel to the grain the pieces are first annealed by heating at 660 to 750 deg. fahr. in order to avoid cracking.

The heat treatment is conducted by heating the welded assembly at about 925 deg. fahr. for 15 min., quenching, usually in air to mitigate distortion, and aging at room temperature for 4 days. The efficiency of welded joints, heat-treated, and not dressed, varies from 50 to 100 per cent of the specified strength (55,000 lb. per sq. in.) of the material. After dressing, this efficiency range becomes 25 to 80 per cent. The welds are quite brittle and will not withstand bending.

Magnesium and its alloys are not readily welded, because of their rapid oxidation. The chloride fluxes usually employed stimulate corrosion, and welds that appear to be satisfactory immediately after welding gradually exude a white deposit which spreads. Quite generally the broken welds are drossy and often contain gas cavities.

Brazing in Aircraft Construction

The practice of brazing as applied to aircraft construction is principally in connection with the manufacture of fittings. The Air Service requires dip brazing wherever practicable, because the operating temperatures can be better controlled and the results are more uniform. As a rule, flame brazing is permitted on the basis of conclusive demonstration by actual tests showing that the manufacturer's method is reliable. Oxyacetylene brazing is generally prohibited. Aeronautical Process Specification No. 17 of the Bureau of Aeronautics, Navy Department, for brazing is an excellent one and consultation should also be made of Air Service Specification No. 20,003.

Mild-carbon (1025), chrome-vanadium (6123 and 6130) sheet, and chrome-molybdenum tubing can be brazed satisfactorily. Nickel-steel bar and tube, however, have given considerable trouble on account of cracking. Chrome-vanadium steel may be brazed to chrome-molybdenum tubing without difficulty.

Brazing Material. The standard Air Service brazing mixture consists of a high-copper, high-melting-point brass selected to insure minimum softening at the quenching temperature (1625 deg. fahr.), which is used in the heat treatment of brazed chrome-vanadium and chrome-molybdenum steels. The analysis of this brazing alloy is given in Table 5.

TABLE 5 AIR SERVICE REQUIREMENTS FOR BRAZING MATERIAL

	Chemical Composition				
Material	Copper	Lead	Tin	Iron	Zinc
Brazing	79.0–82.0	0.20 (Max.)	None	0.10 (Max.)	Remainder

This alloy can be purchased in the form of wire for flame brazing or as ingot for dip brazing. It is wholly molten at about 1830 deg. fahr., but it starts to melt at about 1750 deg. fahr. Alloys of lower melting point, containing less copper, give satisfactory joints and can be used, provided there is no heat treatment after brazing. Two commonly used mixtures are the 70 copper–30 zinc and the 50 copper–50 zinc alloys.

Preparation of Steel before Brazing. The parts to be brazed should be fastened firmly and closely by riveting, tack welding, or spot welding. Riveting is preferred, as it does not cause scale formation. Tack welding must be carefully done to prevent cracking at the edges of the weld through unequal expansion of the member pieces. Tack welding necessitates pickling to remove the scale formed. Spot welding, with careful manipulation, has proved to be quite satisfactory, for it localizes the heating and engenders little scale formation.

Before the parts are brazed, all oil, grease, or paint should be removed with benzol or a hot caustic soda solution (followed by rinsing in water) and the metal pickled in a warmed aqueous solution of 10 per cent sulphuric or 25 per cent hydrochloric acid for about 10 minutes. The parts are next rinsed in water, dipped in dilute caustic or lime to neutralize any remaining acid, and finally washed in clean hot water.

Preheating for Brazing. Prior to the brazing operation proper, it is necessary to preheat the steel parts slowly to a temperature close to that of brazing in order to avoid cracking from a too rapid change in their temperature. The preheating operation is not easily controlled in flame brazing, but close regulation is possible with dip brazing, in which a bath of borax-boric acid flux or a furnace at about 1300 deg. fahr. may be utilized.

If facilities are available, the best method is to preheat the parts slowly from 800 to 1000 deg. fahr. in a muffle furnace. The parts are held at this latter temperature for about 20 minutes and are then transferred successively to two baths of molten flux at temperatures of 1300 and 1600 deg. fahr., respectively, and are held at these two temperatures for five minutes.

Fluxing. The flux in flame brazing is borax or boric acid, applied in powder form; but in dip brazing the flux is in the form of a bath from 2 to 4 in. thick, floating on top of the molten brazing bath. The best flux composition contains 2 parts of borax and 1 part of boric acid. The flux cleans the steel of oxide and will penetrate into a tight joint when heated to the temperature of the brazing bath. The layer of flux on parts as withdrawn from the brazing bath promotes slow, uniform cooling and prevents oxidation of the steel during this period.

The Brazing Proper. Brazing with 80–20 brass is accomplished at a temperature of about 1850 deg. fahr. Flame brazing requires great skill on the part of the operator and is done with a blowtorch and not with an oxyacetylene flame, by which zinc may be volatilized or thin stock burned through. In the case of dip brazing, the parts should be lowered slowly and remain submerged in the molten brass for about three minutes. They should then be raised and lowered several times so that they will pass through the cleansing flux on top of the bath. After another minute in the brass they are withdrawn. Steel is weak at the brazing temperature and must be handled with care to avoid damage. The brass should drip freely from the steel and be of good yellow color.

After the parts have been brazed, it is advisable to cool slowly and uniformly to prevent cracking. The fittings may be cooled either in lime or on top of a hot furnace, or to blackness in one which is at a temperature of about 1000 deg. fahr., subsequent cooling to be performed in air. Cracking during brazing may be caused either by tack welding, by too rapid heating to or cooling from the brazing temperature, or by the presence of sharp corners or changes in cross-sectional dimensions. Threads are best cut after brazing. The alloy steels are much more susceptible to cracking than the plain-carbon steels. Careful design, proper selection of materials, and suitable conduct of the brazing operation serve to minimize rejections.

Flux is removed from brazed fittings through immersion in boiling 10 per cent aqueous caustic soda solution. The final operation consists of washing in hot water.

Excess brass may be stripped from fittings electrolytically. Joints are preserved during this treatment by coating with paraffin. A 20 per cent aqueous sodium silicate solution carrying about 20 per cent of powdered Acheson graphite dried on the parts will prevent molten brass from taking to the steel.

Properties of Brazed Joints

Tubular joints which have been brazed correctly should be equivalent to welded joints, so that the selection of the process rests upon

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expediency and cost. Since the area to be brazed must be large, tube supports usually require considerable machining.

Microstructure. In Figs. 5 and 6 are shown at low and at high magnification the appearance of a joint in 1020 steel brazed with 80–20 brass. The latter figure shows the intergranular penetration of the alloy formed by the union of the brass and the steel.

Mechanical Properties. The Handbook of Instructions for Airplane Designers notes the following facts:

The strength of a brazed joint depends upon the surface area of the joint and the clearance between the parts to be joined. A brazing mixture may

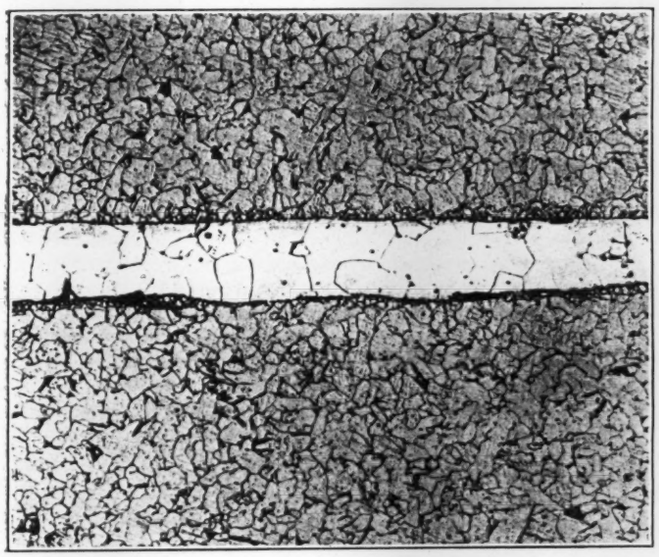

FIG. 5 STRUCTURE OF BRAZED STEEL JOINT (MAGNIFICATION × 100)

have a shearing strength as high as 40,000 lb. per sq. in., but this strength is influenced by several factors which enter into the operation of making the joint and, therefore, should not be used in design. A shearing strength of 20,000 lb. per sq. in. is more conservative; but this may be as low as 10,000 lb. per sq. in. where the brazed joint is in tension in bending. Here there is a tendency to strip the joint, as the concentration of stress is greatest at the edges, where the mixture is weakest due to oxidation. The strongest joint is one in which the brazing mixture is drawn in by capillary action; therefore the limits on the component parts of the joint should be held as close as possible.

SOLDERING IN AIRCRAFT CONSTRUCTION

Some use is found for silver (hard) solder, of high melting point and for soft solders of tin-lead or of tin-zinc base, of low melting point. The soft solders may be generally used without affecting the composition of the parts to be joined, but their use is not proper when the raising of the temperature of the structural member to any point up to 800 deg. fahr. will entail damaging alteration of the mechanical properties of this member.

The general technic for the various types of soldering is uniform. Regardless of the nature of the solder, all metal surfaces must first be carefully cleaned, mechanically or chemically, prior to the application of the solder. The solder must so be manipulated and the heating so accomplished that a film of minimum possible thickness adheres perfectly to the entirety of the surfaces to be joined. These must fit closely and neatly, and the clearance should not exceed 0.01 in. Excess of solder should be avoided. The use of the oxyacetylene torch is permissible in silver soldering. Soldered assemblies must not be disturbed until the solder has set and they should not be quenched in water or other media to cause rapid setting. Adequate steps must be taken to insure complete removal of corrosive fluxes from the structure.

Silver Solder. The Air Service requirements for silver solder are prescribed in Table 6.

Grade 1 solder is a high-grade silver solder, suitable for general purposes, and grade 2 provides a very high silver content and should be used only where the application demands high strength and good appearance.

TABLE 6 AIR SERVICE REQUIREMENTS FOR SILVER SOLDER

	Chemical Composition					
Material	Silver	Copper	Zinc	Tin	Lead	Other impurities
Grade 1	44.0–50.0	33.3–45.0	9.0–16.6	0.50(Max.)	0.05(Max.)	0.15(Max.)
Grade 2	62.0–68.0	20.0–25.0	12.0–18.0	0.50(Max.)	0.05(Max.)	0.15(Max.)

Silver solder is used for joining iron and copper-base parts, as in gasoline lines, where strength and resistance to vibration are important considerations. It is also employed for parts which are subjected to temperatures exceeding 150 deg. fahr. and where brazing is not desirable. Grade 1 solder has a shearing strength of approximately 38,000 lb. per sq. in. Commercial silver solders have melting points of from about 1400 deg. fahr. upward, depending upon their composition. Boric acid or borax may be used as a flux, and this is removed by washing, after soldering, in hot water. Silver soldering is expensive and is not extensively employed.

Tin-Lead Solder. The Air Service requirements for tin-lead solder are set forth in Table 7. This 50–50 (half and half) solder is used for wrapped terminals and for general soldering purposes (tinned, zinked, and terne-plated steel, and copper and brass). It is not to be used for filling in cracks or surface im-

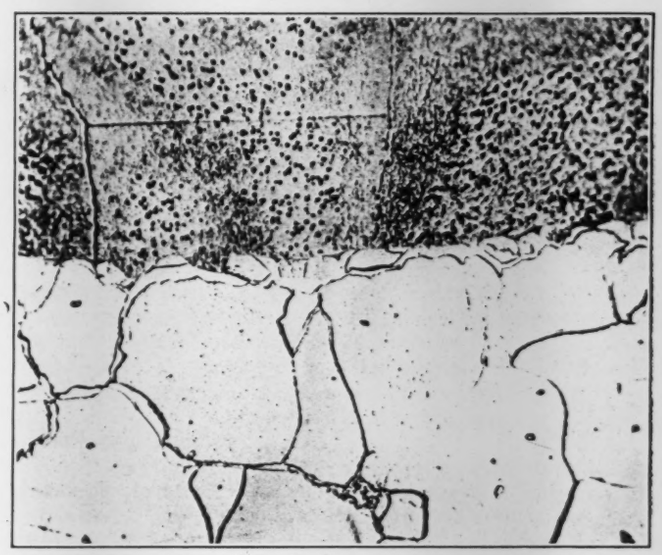

FIG. 6 COMPOSITE METALLOGRAPH OF JOINT SHOWN IN FIG. 5, AT HIGHER MAGNIFICATION, 80–20 BRASS ABOVE, 1020 STEEL BELOW (MAGNIFICATION × 1000)

perfections. It is to be made from new tin and commercially pure lead. Its melting point is about 410 deg. fahr.

TABLE 7 AIR SERVICE REQUIREMENTS FOR TIN-LEAD SOLDER

	Chemical Composition				
Material	Tin plus lead	Tin	Antimony	Copper	Impurities(a)
Grade A	99.65 (Min.)	46.0 (Min.)	0.25 (Max.)	0.08 (Max.)	None

(a) Sum of zinc, aluminum and cadmium.

In the use of 50–50 solder the parts to be soldered must be freed from scale, oil, oxide film, grease, and foreign matter, then heated and fluxed as the solder enters the joint. The heat for soldering may be furnished by a tinned soldering copper or by a gas burner. When materials are dip soldered, they are first dipped (hot) into a bath of flux and then into the bath of solder, which is kept at approximately 675 deg. fahr. and of such depth that the temperature change caused by immersion of parts is negligible. The dross is removed from the surface of the bath before each dip.

There are many fluxes on the market, but the Air Service sets the following specifications:

1 The flux for electrical conductors shall be in the form of a paste manufactured by mixing petrolatum, zinc chloride, and ammonium chloride or suitable equivalents. It shall not flow below 100 deg. fahr. and shall be neutral or only slightly acid in reaction and free from resin;

2 The flux used for soldering wrapped cable terminals shall be a stearic acid or suitable alkaline mixture of stearic acid and resin or resin dissolved in alcohol or other approved solvents;

3 For the soldering of miscellaneous parts, any commercial flux may be used which will give a clean surface and which contains no free mineral acids.

Immediately after soldering, the joints should be washed in hot water and then with a hot aqueous solution of soda ash or a 10 per cent aqueous caustic solution. Whenever possible the washing should be done by complete immersion of the soldered joint. The cleaning solution should at all times show an alkaline reaction with litmus paper. The alkaline cleaning solution should finally be removed by washing the parts in hot water. The rusting of aircraft accessories, caused by improper removal of flux, has given considerable trouble.

A shearing strength of about 6000 lb. per sq. in. may be expected of tin-lead soldered joints. It should be remembered, however, that this solder has practically no proportional limit and, therefore, will slip under a load applied for a long period of time.

Aluminum Solder. The 70 tin–30 zinc solder (and its related alloys containing such added elements as aluminum, copper, lead, magnesium, phosphorus, and antimony), employed for aluminum sheet adheres fairly well, but does not flow readily into joints. The surfaces to be soldered are cleaned, scraped, and tinned, after which solder may be sweated into the joint by applying heat behind the joint. Sometimes the aluminum is tinned with the 70–30 alloy and used in conjunction with the more fluid 50 tin–50 lead solder, which is sweated into the joint. The 70–30 alloy melts at about 480 deg. fahr. The ultimate strength in shear of a joint soldered with 70-30 stick should be not less than 7000 lb. per sq. in.

On the whole, the present aluminum solders are not satisfactory; and the situation with reference to a solder for duralumin is even more unsettled. The requirements for the latter, that it adhere and flow well at such a low temperature as will not affect the mechanical properties of the duralumin through drawing, have not been met.

The solders for aluminum and its alloys are electronegative to aluminum, so that a soldered joint is rapidly corroded, just beyond the seam, in the presence of water or of salt vapor. No soldering is permitted on aircraft-engine castings, and even in automotive work it is avoided, whenever possible, in favor of welding.

Railroad Organization

Administration, Organization, and Management Defined—Fundamental Differences Distinguishing the Railroad Industry—Methods of Controlling Business—Functional Organization—Methods of Organization—Coördinating Work of Various Departments

By J. C. CLARK,[1] NEW YORK, N. Y.

"ADMINISTRATION," "management," and "organization" are terms so closely allied that it is necessary to define each of them in order to discuss any one of them. J. W. Schulze read a paper before the Taylor Society which was published in its Bulletin for June, 1920, page 120, in which he gives the following definitions:

> *Administration*—the function of determining the objectives toward which an organization and its management are to strive, the facilities with which it is to work, and the governing policies and restrictions under which it must work.
>
> *Organization*—a combination of the necessary human beings, materials, tools, equipment, working space, and appurtenances, brought together in systematic and effective correlation, to accomplish some desired object.
>
> *Management*—the function or force responsible for directly conducting the organization toward the objective set up for it, and keeping it within the governing policies imposed upon it by the administrative officials.

Oliver Sheldon in his book, Philosophy of Management, page 32, gives the following definitions:

> Administration is the function in industry concerned in the determination of the corporate policy, the coördination of finance, production and distribution, the settlement of the compass of the organization, and the ultimate control of the executive.
>
> Management proper is the function in industry concerned in the executive policy, within the limits set up by administration, and the employment of the organization for the particular objects set before it.
>
> Organization is the process of so combining the work which individuals or groups have to perform with the faculties necessary for its execution that the duties, so formed, provide the best channels for the efficient, systematic, positive, and coördinated application of the available effort.
>
> .....Administration determines the organization—management uses it. Administration defines the goal—management strives toward it. Organization is the machine of management in its achievement of the ends determined by administration.

These definitions have caused considerable controversy on some of the finer points involved, but in the essential features they correspond very closely. Mr. Schulze's definition of organization includes physical property as well as the human element, while Mr. Sheldon's definition includes only the human factor. It is the human factor that we are dealing with in this paper, and for this reason Mr. Sheldon's definitions seem preferable. These definitions are given to serve as a guide in analyzing railroad organization, and to promote clear thinking during the process.

Fundamental Differences That Distinguish the Railroad Industry

It is the function of the railroad in the modern world to produce transportation by rail, but there are many other lines of business in which the railroads are engaged. Most of these outside interests, however, either help to develop railroad traffic or grow out of necessity to use property owned by the railroads. In discussing railroad organization it is not necessary to include these outside interests, as they are usually conducted more or less separately from the transportation business. On account of the very nature of transportation the railroads are more or less of a monopoly. There are many communities in the United States that are dependent upon only one line of railroad for their transportation service, and anything that hampers its efficiency has a direct effect on all communities that are dependent upon that road for transportation. The only redress a community has is to protest to the railroad management or appeal to the Interstate Commerce Commission or to a state regulating authority. In case two or more railroads serve the same community the monopoly of any one road is not so complete, but even in this case the shipper has a limited choice because shipments for certain destinations can only be made over certain railroads.

Another factor which has a bearing on railroad organization is the fact that railroads are primarily public highways and also common carriers. The Interstate Commerce Commission has pointed out that it is just as much the duty of the Government to see that adequate transportation is provided as it is to construct and maintain public highways, and that it has only delegated the duty of furnishing transportation to private corporations. The right of the Government to regulate common carriers has long been recognized, and has been sustained by an unbroken line of court decisions down to the present time. The fact that the Government exercises such a large measure of control over railroad operation has had in the past and will have in the future a very marked effect upon railroad organization.

Another important consideration is the fact that railroads must be continuously operated. This means, of course, that they must be operated every hour of the day and every day of the year. The busiest time of the twenty-four-hour period for many railroads is the time when most other industries have closed for the day. Night work and irregular shifts for large groups of employees must be taken into account in building up a railroad organization.

Inasmuch as the Federal Government has delegated to private corporations the function of providing adequate transportation, the profit incentive is present in the railroad business as in other corporate enterprises. In any business venture it is essential to make a profit if the concern is to maintain its credit and be enabled to make additions to its property that are necessary for the proper conduct of its business; but in the railroad industry, due to the nature of its business, profit is secondary to service, and a great many cases could be pointed out where railroad corporations are compelled to operate parts of their lines at an actual loss.

Business Control

In the foregoing paragraphs, the author has attempted to outline a few of the fundamental differences that distinguish the railroad industry. The next question is: What kind of an organization conducts the railroad business? In approaching this question it seems best to work from the top down. As in any other corporation the control, in theory at least, is exercised by the owners through a board of directors. The question arises: Who are the owners and how do they control? Due to the fact that over a considerable period of time railroad earnings were comparatively low, railroad credit suffered, and it has been necessary in the past to finance a large part of the additions and betterments to railroad property through the sale of bonds rather than stocks. The result has been that in a great many cases the bonded indebtedness is out of line with the total capitalization. In some cases the funded debt exceeds 75 per cent of the total capitalization. It is recognized that this creates a rather serious condition, especially for the stockholders, and makes it doubly difficult to sell new stock. When the funded debt is very high, comparatively slight fluctua-

[1] With Industrial Relations Counselors, Inc., New York, N. Y.

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tions in the net income make a big difference in the rate of return to the stockholders, and, of course, jeopardizes the financial stability of the whole organization. It is evident that a comparatively small part of the total capitalization of our American railroads is in the hands of the stockholders, who are the only ones that have a vote in the control of the business.

Much has been said recently on the subject of non-voting stock. This is a question, however, that will probably not be vital in the railroad industry for the reason that the Interstate Commerce Commission has full authority over the issuance of stock of railroad corporations and the attitude of the Commission seems to indicate that it is not likely to approve the issue of non-voting stock.

There is still the question of control through holding companies and control by minorities. The device of the holding company is so well known that no comment is necessary. It is also well known how a minority ownership may control a corporation through proxies or other methods.

In order to show how control through a board of directors may affect the organization on a large railroad, the recent report of the Interstate Commerce Commission covering the investigation of the financial operation of the Denver & Rio Grande Western is cited. This report was made public July 6, 1926. The following quotation begins on page 155 of this report:

> The reported insolvencies and receiverships summarized in the foregoing recital are all traceable to one source, the assumption in 1905 by the Denver Companies of obligations with respect to the Western Pacific and its securities which were beyond their abilities to fulfil. The enormous losses by stockholders and bondholders and the long period of impaired railroad service followed as the natural economic results of that one ill-advised undertaking.

The report than gives a brief summary of the transactions which wrecked the Denver Companies, and continues:

> In brief, shortly after Missouri Pacific control had been established over them the Denver Companies, theretofore profitably and conservatively managed, were committed to an unwise speculation which was intended to benefit all railroads of the Gould system, whereas its risks would be borne by the Denver Companies alone and its unsuccessful outcome would affect other railroads of the Gould system only to the extent of the 30 per cent stock interest in the Old Denver owned by the Missouri Pacific. That such a situation could have been brought about through ownership of only 30 per cent of a railroad's stock is illustrative of the inequities which were formerly possible within a railroad system controlled through interlocking directorates.

The conditions referred to in these quotations had extended over a period of about 20 years and are not ended yet. During all of this time the territory served by the Denver & Rio Grande Western Railway had been deprived of adequate and safe transportation service. The management and organization of the railroad have been deprived of necessary facilities and the opportunity to give good service. No organization can accomplish its desired objectives under such severe handicaps.

Functional Organization

Board of Directors. The functional organization of a railroad usually begins within the board of directors. Most railroad boards of directors have permanent committees dealing with finance, operation, valuation, traffic, and other important matters. As a general rule, however, these committees do not have power to act, but in some cases they do. Regardless of whether the committee has authority to act or not, when a committee is charged with a certain duty it has a very important influence on the action of the board as a whole.

The board of directors usually holds the president responsible for conducting the business of the railroad within the limits set by the board. The president, in nearly all cases, is a member of the board of directors. Consequently his duties are both administrative and managerial.

Finance Department. The three major functions in the railroad organization are finance, traffic, and operation. The finance or treasury department handles the money; the traffic department gets the business, and, subject to the authority of the Interstate Commerce Commission, fixes the tariffs; and the operating department moves the business. No attempt will be made here to describe the various functions except in a general way. It seems desirable, however, to get some idea of the various functions involved in order to show how the parts of the organization are coördinated.

Some railroads have a vice-president in charge of finance. On these roads the finance department, in addition to handling the funds of the corporation, often has more or less work in connection with issuing stocks and bonds of the corporation. However, all railroad stock and bond issues have to be approved by the Interstate Commerce Commission, and very often these matters are handled by the finance committee of the board of directors with the bankers, and through the general counsel with the Interstate Commerce Commission.

The treasury receives money from agents and conductors, from other railroads, from investments, and some other minor sources. It pays this money out upon proper authorization to employees in the form of wages and salaries and claims, to other railroads to balance interline accounts, to cities, counties, states, and the Federal Government in taxes, to patrons in settlement of claims, to manufacturers and dealers in railroad supplies, and to stockholders and bondholders for dividends and interest. It is quite apparent that the treasury department has a very wide range of contacts, and their activities must be well organized if the best results are to be obtained. Take the matter of the handling and transmittal of money by agents and conductors. If the requirements of the treasury department are unreasonable or burdensome, it may cause serious complaint upon the part of these important groups of employees and result in lack of morale where morale should be maintained at the highest possible point. It is recognized, of course, that the treasury department must see to it that funds are handled and transmitted in a safe and proper manner, but in working out the method to be used consideration must be taken of the conditions surrounding the employee who must live up to the regulations. A great many illustrations could be given to show the importance of the careful coördination of the treasury department with the other departments. In a great majority of cases there is little or no friction on our American railroads in this respect, which speaks very highly for the finance and treasury departments.

Traffic Department. It is the function of the traffic department to develop traffic and also to fix tariffs with the approval of the Interstate Commerce Commission. There are two main ways in which traffic may be increased. The first is by soliciting competitive business, and the second is by developing industry in the territory served by the railroad. The freight or passenger agent soliciting competitive business is practically limited to one argument, which is service. The Interstate Commerce Commission has complete control over rates, and as they are fixed in most cases there is little advantage as between different roads in this respect. American railroads are coming to realize that service can be a very strong argument for securing competitive business. It is the operating department that actually moves the traffic, so that perhaps the main element of service can be provided only by that department. The traffic department, however, does give a very valuable service by keeping the shipper informed as to location of his shipments, and in other ways that do not directly affect the movement of traffic.

For the purpose of developing traffic in the territory served by a railroad there has been established in a good many cases a development bureau within the traffic department. This bureau endeavors to get new industries located on its line and to develop new markets for industries already on its line. It also coöperates with various schools and colleges to develop better methods in farming and in marketing farm produce.

We cannot enter into any discussion of freight rates here, although it is a very important part of the work of the traffic department. The head of the traffic department is usually a vice-president; the next in line are a freight-traffic manager and a passenger-traffic manager. Under these officers are general and district freight and passenger agents, and in most cases traveling freight and passenger agents. There is nothing complicated or unusual about this organization and as a rule it functions very smoothly.

Operating Department. This department is the one that looms the largest in the railroad business. The man at the head of the operating department is a vice-president, or, in some cases, a general manager who reports directly to the president. This officer has

charge of the maintenance of the physical property as well as of its operation. He will therefore have under him one or more general superintendents, a general mechanical superintendent, and a general maintenance-of-way superintendent or engineer. Reporting to the general superintendent will be two or more division superintendents. It is at this point that two types of organization appear. In the so-called divisional organization the division superintendent will have charge of maintenance of way and of structures, maintenance of equipment, and the operation of the division. In the so-called functional organization the division superintendent has no direct authority over maintenance of way, structures, or equipment, the master mechanic and the division engineer reporting to the mechanical superintendent and the engineer maintenance of way, respectively.

We shall consider first the divisional organization. The strong point of this type of organization is the fact that the division superintendent has direct control of both the maintenance of the property and operation on his division within the limits set by higher administrative authority. Under this plan the division superintendent is in close touch with all of the activities, and can more easily secure complete coördination and coöperation between his departments.

Under the functional organization where the division master mechanic reports to the mechanical superintendent and the division engineer reports to the engineer maintenance of way, it is more difficult to get this coördination and coöperation. The tendency is for each department to consider itself as almost a separate business. On the other hand, under the functional organization it is possible to develop a higher degree of efficiency within each department and in many cases there is a very high degree of coöperation between the departments. There are very successful railroad organizations under both types of organization.

There are numerous other functions in a railroad organization that have not been mentioned. It would require a good-sized book to go into details regarding the duties and form of organization of all of these departments. We shall name some of them, however, and give a brief outline of the organization.

Accounting Department. One of the most important functions is that of accounting, and some of the railroads have a vice-president in charge of this work. Under the general auditor there is usually an auditor of disbursements, an auditor of revenues, an auditor of passenger accounts, an auditor of freight accounts, and an auditor of miscellaneous accounts, with an officer at the head of each subdivision with an appropriate title. It is the auditing department that is usually in charge of the work of making most of the reports to the Interstate Commerce Commission. It may be interesting to note that the Interstate Commerce Commission, in its order of July 1, 1914, specified a very definite procedure for all railroad accounting and established approximately 700 different accounts in order to insure uniform accounting on all railroads. These accounts are designed to secure the most minute information for the Interstate Commerce Commission. There are several volumes available giving complete information on railroad accounting. The author mentions this because he believes most railroad officers outside of the accounting department should be better informed regarding the accounting requirements of the Interstate Commerce Commission. It has a very definite bearing on the organization of the accounting department and the relationship between the accounting department and all other departments.

Legal Department. This department has a very important function in railroad organization. A large railroad system will operate in 12 or 14 different states. Every state has its own laws to be observed, and in addition to this there are numerous federal laws to be lived up to. It would be an impossible task for the legal department on any railroad to familiarize every employee with the various state and national laws so it becomes necessary for the legal department to carefully scrutinize all rules for the government of employees to see that they conform with all existing laws, and in this way employees who might violate laws in the performance of their duties are controlled. In addition to this phase of the legal department work, they also have to defend their railroad against all kinds of damage suits and other legal actions. The claims departments of most railroads are under the legal department. There is a general claims agent who handles personal-injury claims, stock claims, and, in fact, every character of claims except freight claims, which are handled in a separate department by a freight claim agent.

Another very important function which usually comes within the jurisdiction of the legal department is that of handling matters of taxation. The tax agent on a railroad has rather an important job as taxes are one of the large items of expense. It is complicated by the fact that railroad property extends in narrow strips through all of the cities, counties, and states in its territory, which means that every local taxing political unit is levying taxes against the railroad. The result is that the railroad is compelled to protect itself by a careful examination of all taxes levied. Closely allied with the tax question is the handling of real estate. Railroads necessarily hold a considerable amount of such property. In some cases the real-estate and taxation departments are one. In other cases the real estate is handled under a separate department.

Valuation Department. There is another function on the railroad that has assumed great importance within the last 15 years. This is the question of valuation. In 1914 Congress passed a law requiring the Interstate Commerce Commission to place a valuation on all railroad property used for transportation as the basis for fixing reasonable freight and passenger tariffs. The Interstate Commerce Commission organized parties usually under the supervision of engineers who made a complete inventory of all railroad property in the United States. This work at the present time is incomplete, although the Commission has fixed a tentative valuation in most cases. There is a wide difference of opinion as to what principles should be adopted in determining valuation for rate-making purposes. In order to handle questions affecting valuation in the best way possible a great many railroads have established a valuation department, often under the immediate supervision of a vice-president.

Medical Department. This department performs an important function on the railroad. Due to the fact that the swift movement of trains is hazardous it is very important that all employees having anything whatever to do with train movement should be physically qualified to perform their duties. Physical examinations were established on practically all railroads twenty-five or more years ago. In addition to the initial physical examination, employees in train and engine service are required to pass periodic examinations, especially for eyesight and hearing. The medical department also must hold itself in readiness to give medical and surgical attention in case of accidents. Claims usually grow out of accidents. Therefore the medical department must coöperate with the claims department by furnishing exact information as to the extent and nature of injuries to persons. The medical department on a railroad is usually organized under the general manager, but in some cases it is organized directly under the claims department, and in other cases under the relief department.

METHODS OF ORGANIZATION

There are other functions too numerous to mention or describe here. Outside of the main functions that have been described there is considerable variation in the method of organization. For example, the safety department; on some railroads this department is organized under the general manager; elsewhere it may be organized within the claims department, or within the insurance department, so that there is a wide difference in this respect. The main point to be made here is that an organization is essentially human and it must be built up with the full realization that every job within it is to be filled by a human being who is subject to all of the instincts, passions, and prejudices inherent in human nature.

In planning or developing an organization for a railroad, it seems essential to make what might be called "vertical and horizontal divisions." The work to be done usually divides itself more or less naturally into functions, and these functions would be the vertical divisions. As the business of a corporation grows it is the tendency for functions to grow in number and in importance. On some of our large railroads there are twelve or more vice-presidents, each in charge of a separate function, while on the smaller roads there may be only two or three vice-presidents, each having charge of several functions. For this reason there is usually a better opportunity for managers on the smaller lines to secure a wider range of knowledge, and consequently a better understanding of relationship between the various functions. On the other hand, a large

enterprise makes it absolutely essential that the highest-trained experts be placed in charge of the various functions if the best results are to be obtained, and in the larger companies this is usually done, with the result, however, that it is more difficult properly to coördinate the work of the various functions and to secure proper coöperation between the heads of the departments. The tendency is quite natural for each department head to emphasize the importance of his own function, and in some cases the various functions are looked upon as almost a separate business. Each department head should be held strictly accountable for the operation of his particular function or department. At the same time he should be made to realize that he is only a part of the great enterprise and that in many situations it is essential for some of the departments to subordinate their interests to others. The author has in mind certain cases where the accounting and legal departments have been able to emphasize the importance of their functions to the point where unreasonable restrictions and requirements were enforced on other departments.

The horizontal division of the organization indicates how much authority any one official should exercise and how much can be delegated to subordinates; how much detail can be loaded on to any given position and still leave the holder of the position sufficient time for supervision and other matters. It is obvious that no two men are equally capable of handling detail and supervision. It follows that changes in personnel, which are constantly occurring, very often require changes in the organization set-up. It is quite evident that a human organization in order to be effective must be elastic. It is also quite evident that changes in organization made necessary by changing personnel or changing conditions, should be given very careful consideration. The duties of a position of importance should be fairly well defined, and there should be a very clear understanding of the limits of authority and responsibility. It is not essential, and in the author's opinion not desirable, to have all these duties and responsibilities expressed in writing, but it is desirable and essential that every officer should have a very clear understanding with his superior in this respect.

The author recently talked with a responsible railroad official who stated that he had never discussed with his superior the duties and responsibilities of his own position and, in fact, had not given much consideration to the matter himself except as various matters which came to his attention forced it upon him. This officer made the statement that after two years in his present position he had no clear understanding of his duties and responsibilities, and that he could assume responsibilities that seemed to be entirely out of his department, and in some cases he had done this because he felt that the good of the service required it.

In many cases officers in responsible positions are not allowed to appoint their subordinates without interference from their superior officers. The proper consideration of appointments in any organization is most important. If the head of a minor department is to be held responsible for the operation of that department, he must be given a pretty wide authority in the matter of appointments. If some one higher up in an organization makes appointments that the official responsible for the department does not approve, he can say with a good deal of reason that he is not responsible for results because he was not permitted to make the appointments which he considered best.

Coördinating Work of the Various Departments

In planning an organization or in making changes in an established organization very careful consideration must be given to the question of coördinating the work of the various functions or departments. It is often essential to have points of contact between officers in the various departments who are far below the rank of department heads. If these subordinate officers are permitted to develop these promiscuous contacts it may, and often does, result in the entire organization being thrown out of harmony. On the other hand, if the plan of the organization does not provide for contacts except between department heads the whole organization is likely to be so cumbersome that efficient functioning is impossible. Proper coördination has a very definite bearing on coöperation. Unless the functions within an organization have been properly coördinated it is practically impossible to secure coöperation between the officers in the various departments.

Railroad transportation is absolutely essential to the prosperity of our country. The more efficient transportation becomes the more prosperous our country should be. The mechanical development in railroading has been very rapid and the saving effected through the use of modern locomotives and modern machines of every kind is really marvelous; but the human organization has not kept pace with mechanical development, and today the great opportunity for advancement lies in the careful study of organization, the analyzing of every official and non-official position to see what type of man can best fill the given positions, and then selecting and training men for the work. The first job, however, is to make sure of proper organization. No matter what policy be adopted by administration, that policy cannot be carried into effect by management except through efficient organization.

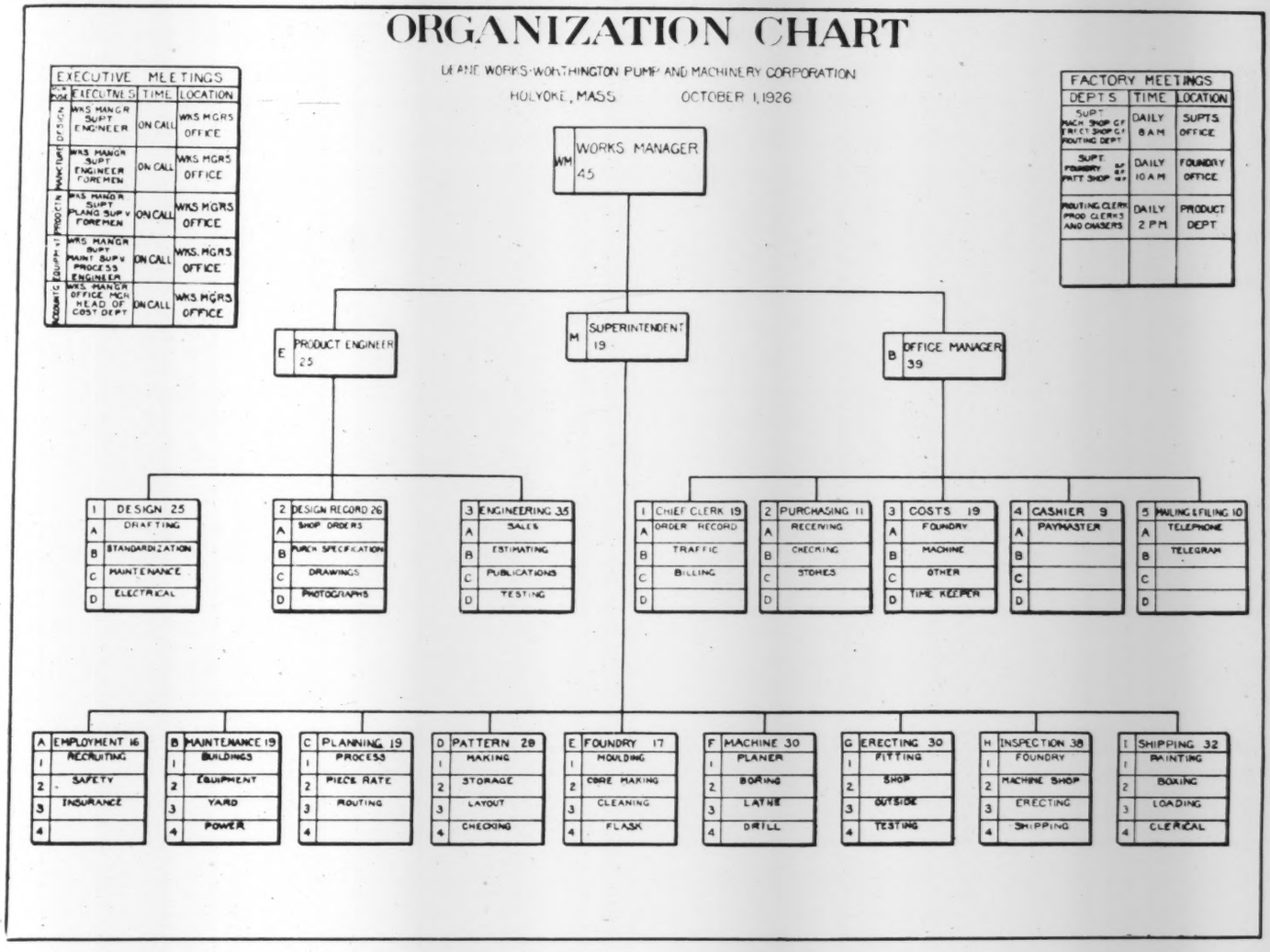

FIG. 1 CHART REPRESENTING ONE UNIT OF A DECENTRALIZED MANUFACTURING ORGANIZATION
(Note figures under or at right of title denoting length of service of present incumbent.)

Vitalizing vs. Centralizing Organizations

Disadvantages of Concentration and Advantages of Discreet Decentralization

BY ROBERT E. NEWCOMB,[1] HOLYOKE, MASS.

MARK TWAIN said, "Everybody complains about the weather, but nobody does anything about it." Administrators complain about incompetent subordinates, but what is being done about it? Doesn't the administrator accuse himself most severely while condemning the incompetence of subordinates?

The administrator is quite as incompetent as his subordinates, if not more so. Business administration as a profession has lacked a time-tested background of tradition, and may profitably appropriate some of the fundamental policies of the professional administrators of armies or states. The series of papers sponsored at this meeting by the Management Division will, it is hoped, help elevate to a profession the arts of management, administration, and organization. The business administrator organizes, starts, or carries on a business; the fundamentals of an organization are personnel, training, and morale.

The personnel is of first importance: it is the mass of raw material to be welded into an effective organization through training and development of morale. Hence the additions to personnel should be tested with a mental motion picture of the annual future progress and development of the individual, rejecting those who do not year after year fit into the picture. The subtractions from personnel should be made with great reluctance and in each case first tested with a review of the individual's service, conserving all the skill, experience, and unwritten knowledge that one may, by continued service, pass on, thus insuring a permanent organization.

Training is only second to personnel, as it develops intelligent application of the talents. A trained force inspires the administrator's confidence. The confident administrator deputizes others subordinating detail and working with intelligence and joy as well as with energy. This deputizing stimulates the development of both executive and subordinate for greater responsibilities and improvement in morale.

Morale is a third important factor of organization, that intangible element which carries the beaten gladiator on to victory against seemingly overwhelming odds. The morale of an organization is developed by delegating tasks to tax, but not overload, the individual. Red tape and deterioration of morale follow in the wake of centralization, sapping loyalty, initiative, and enthusiasm.

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[1] Superintendent, Deane Works, Worthington Pump and Machy. Corp. Mem. A.S.M.E.

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Concentration of administrative functions burdens the principal executives with details, stunting their growth and curtailing the development of subordinates. The delegation of responsibilities tests and seasons the lower ranks for new and added responsibilities. Concentration removes the executives from the local contacts necessary to qualify for the proper administration of local functions.

Consolidation and centralization is the order of the day, with local administrative contact lost, executive personality subordinated, and the thrilling days of the Captains of Industry gone. Red tape, routine, etc., masquerading as scientific management become the law and habit, destroying morale and the joy of being boss.

Real scientific management is organized with less thought as to form of organization, and more to vitalize as well as systematize. The progressive consolidation and centralization of administrative functions has in the past developed a general trend toward more economic organization. Malpractices have developed rapidly, so it is well now to review and consolidate the gains, and eliminate the evils of this transition period.

Some of the larger and more progressive of our industries, The General Motors Corporation, for example, have especially prospered through the decentralized individuality of the separate companies, taking advantage of central control for coördinating general policies. The thriving activity of the independent textile and paper mills of New England compared to their big brothers further illustrates the sound policy of decentralization.

In the German army the art of administration has been raised to a profession. Here one might expect the business administrator would find authority for centralization, but let Prof. Edward D. Jones quote the German General Staff and War College:

> The distance separating the several divisions of a great army . . . . makes it impossible that highly centralized control should exist.
>
> Headquarters are responsible only for the general features of the plan of operation. . . . .
>
> Authority immediately passes down the line to army commanders and regimental and company officers, lodging as close as possible to the time, place, and agencies of specific action.

Again,

> It is reported that Von Moltke once said that nothing should be ordered which it was conceivable could be carried out by the proper officers without orders.

Professor Jones further states:

> As organizations grow, one function after another should take its departure from headquarters and pass down the line of administration, drawn to lower levels by the necessity of keeping in touch with local condition. . . . .The progress of an organization is largely due to the ambitious upward pressure of the ranks below. Judicious liberty will increase this pressure, and form a prime means of insuring the future.

The accompanying diagram (Fig. 1) represents one unit of a decentralized manufacturing organization. This manufacturing unit is a line type of organization, involving about five hundred employees. Intimate relations and conferences promote cross-fertilization with the perfected accomplishments of the experts of a line-and-staff organization.

The careful selection of personnel, with years of experience (see figures inserted under position title in diagram) and training at this plant, has developed subordinates and an organization vitalized with personality. An administrator without local contacts cannot hope to vitalize or inspire an organization to efficient efforts. Organizations are intensely personal, they are the tool of the administrator; concentration at headquarters clogs the management with detail and the organization becomes all bound around and choked with red tape.

Summarized, concentration is desirable for coördination only—beyond that it is strangulation while discreet decentralization vitalizes an organization. Centralization frequently retards decisive action until the opportune time for action has passed. The initiative in competitive sales and manufacturing effort is lost and destroyed as a result of delayed decisions. Loss of decisive action and initiative is reflected in the lowered morale of organizations with the central administrative authority too far removed from local contact.

Administrators applying a sound code of management have more to praise than to criticize in subordinates. Someone has said that "business building is man building" and man building is fundamental to organization building. Man building for continuous constructive business building is seldom in harmony with a centralized organization. Concentration discourages and devitalizes "the ambitious upward pressure of the ranks below."

Well-distributed authority vitalizes with liberty of decision and freedom of initiative and of action. Concentration of administration with its devitalizing red tape is not harmonious with a sound code of management. The administrative function is to coördinate, deputize details and vitalized scientific management follows as a natural consequence of appreciating that an organization is individualistic and human.

Industry's Annual Tax for Materials Handling and Suggestions for Its Elimination

How the National Materials-Handling Bill Can Be Reduced a Billion Dollars a Year by Utilization of Equipment Now Available, Relocation of Stock Rooms, and a Proper Coördination of Production with Equipment for Moving Materials

By HAROLD V. COES,[1] CHICAGO, ILL.

INDUSTRY is annually spending millions of dollars in payroll for work that could be better, more efficiently, and less expensively done by materials-handling equipment. The total annual payroll of American manufacturing, according to the latest census available, that of 1923, was $14,017,107,000. A survey made for a leading trade paper indicates that the materials-handling labor cost of American industries in this annual payroll was approximately 22 per cent of this amount, or $3,084,000,000.

It is the author's firm belief that materials-handling equipment now available in the present state of the art, together with rearrangement of equipment, relocation of stock rooms, proper coördination of production with materials-handling equipment systems, and adequate plans for procedure and operation in this coördination would reduce this at least to $2,000,000,000, releasing the recipients of $1,084,000,000 of payroll from back-breaking, nerve-racking, fatiguing work to be employed in more pleasant, less exhausting places, in other phases of industry, or in industries perhaps not yet born but awaiting the labor to develop them.

If we assume the average annual wage for this class of work at $1000, then the labor released would be 1,084,000 workers. Suppose we exercise our imagination and, to be reasonably conservative, assume that to release this labor we must invest its equivalent annual rate for one year in materials-handling equipment, what have we done to the annual American industrial balance sheet?

We have transferred an annual expense of $1,084,000,000 from our overhead to our assets, as represented by the $1,084,000,000 invested in equipment, etc. The annual bill for fixed charges and operating expenses would probably not be, on the most conservative basis, over 33 per cent of the initial investment, or $361,300,000, so our national industrial balance sheet would show overhead reduced from $3,084,000,000 to $2,361,300,000, and our capital account increased by $1,084,000,000. The entire investment would probably be paid for out of earnings, i.e., net savings in labor expense, in from four and one-half to five years as an average.

This is not an impossible program at all. It is simply spot-checking our industrial situation and applying the results obtained from the checking to our national situation.

Does this not appear to be a real opportunity for the engineer? Is it not apparent that we have not even scratched the surface as yet?

If the Materials Handling Division were to appoint a committee to work with some of the trade papers, which have been doing good work in bringing home to the industries the sources and cause of this waste with a view to cutting down this expenditure of $3,084,000,000, it would be taking a constructive step forward in enabling engineers, trade associations, etc. to correct the difficulties and to apply the remedies needed.

Now handling costs appear in several places, or rather can be isolated from several places in the cost of sales, as a rule—

1 In the factory overhead, or burden—
- *a* As a cost for handling raw materials, process materials, finished materials and the like
- *b* As fixed charges on fixed assets (rendered more productive)
  1. Output per square foot of floor space (increased production)
  2. Increased working capital (released from work in process).

2 In handling costs concealed in productive labor, in picking up and putting down, getting materials from store or stock rooms located adjacent to or in production centers, and taking finished or semi-finished materials out of machines and moving to the next process point, or to finished-stock collection points, as the case may be.

In those industries where the cost of raw material constitutes nearly half of the cost of sales, direct labor only 10 per cent of the cost of sales, and the remainder is overhead expense, real opportunities for cost diminution lie in the reduction of wasted material, better purchasing, and the reduction of overhead expense; materials handling being one of the large items in this overhead expense.

Because the greater portion of this materials-handling expense is usually buried in the expense payroll and does not stare one in the face, makes the revelations, after a careful survey of all the factors, so startling.

A manager might not know, for instance, that his materials-handling costs per unit of product were, for example, 10 cents; that they might be reduced to, say, 5 cents, or even 2 cents in a concrete case, and that this reduction could be obtained by a capital investment that was within reason.

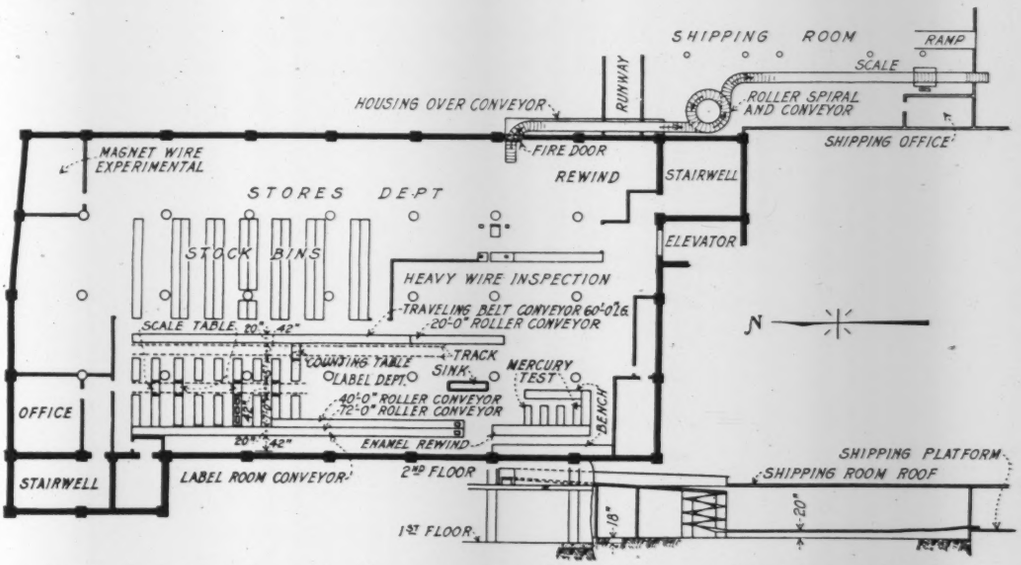

FIG. 1 LAYOUT OF CONVEYOR SYSTEMS FOR LABEL DEPARTMENT AND STOCK ROOM TO SHIPPING DEPARTMENT, BELDEN MFG. CO., CHICAGO

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[1] Vice-President and General Manager, Belden Manufacturing Company. Mem. A.S.M.E.

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Since the greater portion of the total materials-handling labor is treated as an expense, it thus gets into the unit cost of production by way of the overhead or burden. Hence if this overhead is reduced the unit costs are subsequently reduced.

One of the reasons why industry is paying for materials-handling equipment by means of the payroll is the fact that a yearly payroll is paid out monthly, semi-monthly, or weekly as the case may be, but a bill or statement for a piece of equipment shows up as one lump sum; unless the facts are uncovered with a suitable means of evaluating them and a comparative economic measure obtained, the real economies are not apparent and therefore not sought for.

It is amazing how many places there are in an industrial plant where careful studies of materials handling reveal literally gold mines. A manufacturer will spend thousands on new productive equipment that in many instances reduces the prime cost per unit produced a comparatively small amount. In many instances this is entirely legitimate, but he should not overlook the greater opportunities of reducing the overhead by methods similar to those that will subsequently be discussed.

Mr. Charles Piez, in an article entitled What Mechanical Handling Has Done and Is Doing for Industry, in the August, 1926, issue of *Industrial Management*, summarizes very succinctly the development in mechanical handling. To quote therefrom:

> Mechanical-handling installations were auxiliary to the scheme of manufacture, rather than a vital and component part of it, forty years ago. As the art advanced, increasing opportunities for the profitable employment of mechanical handling presented themselves and labor saving in industry became of paramount interest.
>
> This resulted in the mechanical handling of coal. The cement industry was one of the first to incorporate mechanical handling as a vital factor in a continuous process of manufacture; then the steel industry, flour mills, and grain elevators, packing plants, and the lumber industry.
>
> The wide gap between the wages of skilled and unskilled labor that existed before the war has materially closed since. Wages of unskilled labor have advanced considerably more than the cost of the machinery used in mechanical handling. Profits of modern industry depend on the extent to which the cost of moving materials can be reduced.
>
> Mechanical-handling equipment reduces the idle time of the productive equipment and converts the process from an intermittently operated one to a continuously operated one.
>
> It is interesting to note that the amount of power that is available for productive processes has materially increased in the last quarter century, but the amount of power which has been applied to the movement of the raw, partly finished and finished products through our factories has not increased in anything like the same proportion.
>
> The Direct Labor, or that applied to the production of the product, has grown less. The Indirect Labor, or that applied to the movement of the materials that enter the product, has remained about the same.
>
> Certain industries have already lent themselves readily to the installation of labor-saving appliances, such as have already been referred to, and in those industries the volume to be handled was large and the processes were continuous, and the materials lent themselves rather readily to handling by mechanical means. Consequently the systems of handling developed in these industries have practically been accepted as standard and are of universal application.
>
> Other industries have presented great difficulties to a profitable solution of their handling problems. The volume is uncertain, machining and assembling operations are varied so that continuity of operation seems out of the question, and a successful handling system seems too costly to be considered. But wherever there is a large volume of repetitive work, handling processes can be much improved and material saving effected.
>
> A good procedure in building up a business is not to increase production by taking it out of the bone and marrow of the men, but by taking it out of the managerial mind in better methods.

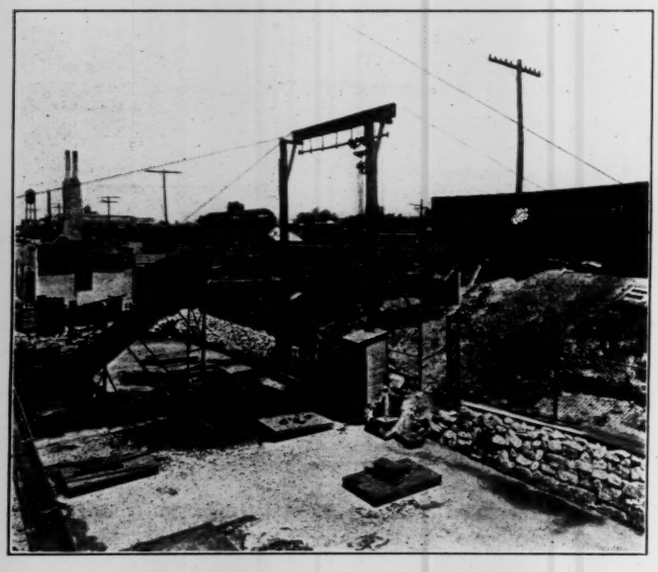

Fig. 2 Conveying System for Handling Coal from Railroad Cars to Bunkers in Boiler House

Industrial Management, in the same issue of August, 1926, makes the statement that "moving is 90 per cent of making, and in this 90 per cent handling margin lies a most productive field for waste elimination and profit building." It is therefore of prime importance to make detailed analyses and assemblage of cost figures to determine just what the materials-handling expenses under the prevailing methods are; then to consider what the possibilities and labor savings are by the adaptation of standard equipment that is available on the market. The application of the Materials Handling Formulas as developed by the Materials Handling Division of The American Society of Mechanical Engineers will then give a measure of the justifiable investment. The various pieces of equipment that are available can then be studied to ascertain how they meet the conditions, tested out under the formulas, their relative economic position determined, and a proper selection made.

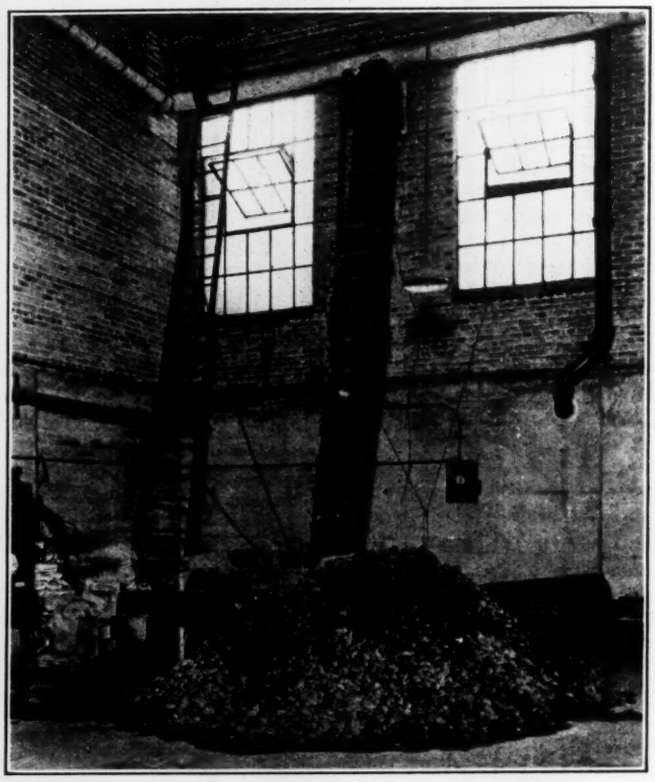

Fig. 3 Ash-Handling System from Boiler House to Trucks or Cars

In order to prove his general statements the author will cite the variety of materials-handling equipment that has been profitably put to use in the works of the concern with which he is connected.

The materials-handling systems installed within the last two years at the plants of the Belden Manufacturing Company are as follows:

1. A conveying system for handling coal from the railroad car to the bunkers in the boiler house
2. An ash-handling system from the boiler house to trucks or carts
3. A small battery truck for handling copper rod and coils in the wire mill
4. A larger battery truck to charge the rubber vulcanizers and to do most of the materials handling in the rubber mill

5 A gravity conveyor handling material from the rubber finishing room to the finished stock room
6 A reversible power conveyor from the finished-stock room to the shipping room
7 A roller and power conveyor handling all magnet wire in the inspection and labeling rooms
8 A gravity conveyor from the magnet-wire stock room to the shipping room at the wire mill
9 A reversible power conveyor from the side track to the stores and finished stock room at the wire mill.

The A.S.M.E. formulas for computing the economies of labor-saving equipment were applied individually and on the total equipment before recommendations were made by the general superintendent to the management to purchase the equipment. The total cost of these systems installed was $19,611. The labor saving was $19,800, or equal to the total installed cost of the equipment or 1.6 per cent of our payroll.

Power to operate the systems costs $400 a year; fixed charges on installed cost amount to $6950 annually. No labor-burden savings are shown since none of the labor savings enabled the company to make any direct overhead savings. Fixed charges on replaced equipment are nil, as in every case hand labor only was replaced.

No credit or account was taken for increase in production resulting from the use of this equipment. The installations, however, have made it possible to speed up shipments and give better service, and some of the equipment has enabled the company to reduce its work in process inventory. No credit for the fixed charges on released working capital, however, has been taken into consideration.

It is interesting to note that the maximum investment which would return simple interest on the investment, or, in other words, would break even with the hand labor, is $62,843, or better than three times the actual investment.

The yearly profit on the investment resulting from the operation of this equipment is $12,450, or 69.48 per cent. The equipment completely pays for itself out of profits in one year, two and one-half months as a total investment, although individual installations require as much as five and one-quarter years for complete amortization out of their individual earnings.

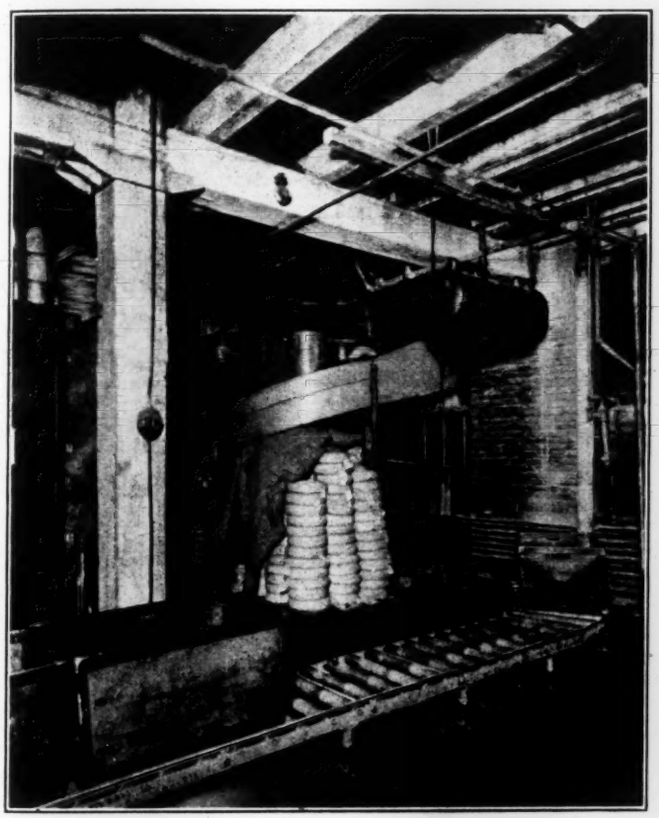

FIG. 4 GRAVITY CONVEYOR HANDLING MATERIAL FROM RUBBER FINISHING ROOM TO FINISHED-STOCK ROOM

FIG. 5 REVERSIBLE POWER CONVEYOR FROM FINISHED-STOCK ROOM TO SHIPPING ROOM

TABLE 1 CONDENSED STATEMENT OF FACTORS IN MATERIALS-HANDLING FORMULAS

	Total cost incl. installation and auxiliary equipment	Annual labor saving	Per cent on investment	Per cent for insurance	Per cent for maintenance	Per cent for depreciation	Cost of power	Overhead annual saving	Replaced-equipment fixed charges	Value of increased production	New equipment fixed charges	Unamortized value less resale value	Maximum investment to return simple interest on investment	Yearly profit from operation	Yearly profit in per cent on investment	Years for complete amortization out of profits
	I	*S*	*A*	*B*	*C*	*D*	*E*	*Ta*	*Tb*	*U*	*Y*	*K*	*Z*	*V*	*P*	*H*
Coal-handling and ash-handling system in heating plant	$ 1618	$ 600	6	2	10	10	$ 40	0	0	0	$ 453	0	$ 1928	$ 107	12.61	4.42
Battery truck in wire mill	2143	3200	6	2	20	17	70	0	0	0	964	0	6955	2164	106.98	0.807
Battery truck in rubber mill	5600	2400	6	2	20	17	100	0	0	0	2520	0	5111	220	2.07	5.24
Finished-stock room to shipping-room conveyor	1450	2400	6	2	8	10	50	0	0	0	377	0	9038	1973	142.07	0.657
Rubber finish to stock-room conveyor	1500	1800	6	2	5	10	0	0	0	0	345	0	7826	1455	103.00	0.885
Label dept. conveyor	2000	Estimated 4000	6	2	8	10	40	0	0	0	520	0	15231	3440	183.00	0.518
Stock-room to shipping-room conveyor	2200	Estimated 3000	6	2	5	10	0	0	0	0	506	0	13944	2494	119.66	0.771
R. R. cars to stores and finished stock to cars	3100	2400	6	2	10	10	100	0	0	0	868	0	8846	1432	52.19	1.61
Totals	$19611	$19800	6	2	12.63	12.76	$400	0	0	0	$6553	0	$67979	$12847	71.51	1.187

NOTE: Factor *X* was taken at 100 per cent of full normal-time operation.

Table 1, which gives a condensed statement of factors in materials-handling formulas as applied to these installations, summarizes the situation fully, and the illustrations help in visualizing the equipment as installed.

In some instances, as in the shipping room and the inspection and labeling rooms, the materials-handling system was laid out so as to tie up with the production and accounting records. Weights, production units, and tonnage figures for production costs and statistical purposes are obtained for this material going by suitable recording points. In the inspection and labeling departments the cross-conveyors are hooked up to the longitudinal roller conveyor and belt conveyor by transfer sections comprised of scale and roller sections, the scale and roller sections acting as a transfer table.

The company manufactures a diversified product; many of its processes are not continuous, but of the intermittent type. The author has not mentioned numerous pieces of equipment such as hand transveyors, manual- and power-operated hoists, and the like, many of which operate in conjunction with the handling systems described.

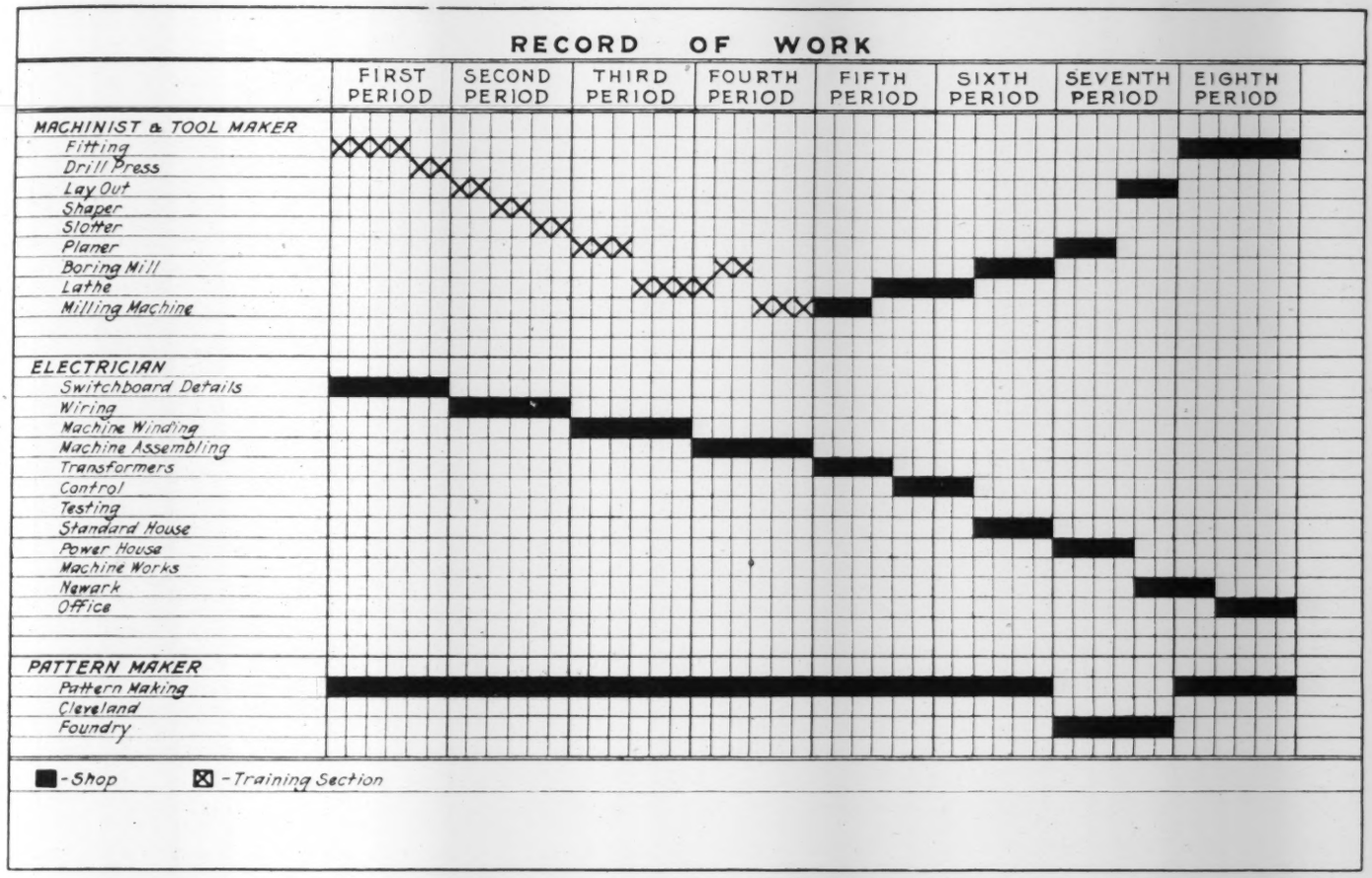

FIG. 1 RECORD OF WORK IN MACHINIST AND TOOLMAKER, ELECTRICIAN AND PATTERN MAKER COURSES

Trades Training

BY CARL S. COLER,[1] EAST PITTSBURGH, PA.

Trades training is a responsibility of management.

This paper deals with the "how" of apprentice training, rather than the "why." It outlines the methods which have been used in promoting trades training by the Westinghouse Electric & Manufacturing Company.

The development of incentives as an important phase of modern apprenticeship is pointed out.

The conclusion is drawn that apprenticeship programs can be economically operated under present conditions without discounting such items as good will and the potential value of exceptional ability which may be discovered or developed.

PROBLEMS of personnel are daily becoming of greater importance to the engineer and the industrial executive. The density of population in industrial centers, the increased size and complexity of industrial organization, and the tendency toward specialization in work, are contributing causes. There is no problem of greater importance to the future of industry and commerce than that of insuring an adequate supply of skilled artisans and practical leaders.

The industrial working force may be divided into two parts: the one, a stable group developed from the ground up and composed of individuals who are actuated by the incentive of steady employment and promotion; the other, a variable, transient group, recruited from without and composed of individuals who migrate easily and who are actuated by the incentive of wages. The members of this latter group are usually trained on the job, although, in periods of very rapid increase of the working force, the vestibule school is sometimes used as a means of separating the instruction from production. The members of the more stable group must be systematically developed.

This paper deals particularly with the methods of training which have been found effective in adjusting the old apprenticeship system to modern conditions.

ORGANIZATION

A separate department, charged with the responsibility of training a selected group of employees for the more responsible positions in the organization, is desirable for the following reasons:

1 It centralizes the responsibility for the work

2 It enables a separation of the functions of production and training when the objectives sought are incompatible

3 It draws a definite economic and psychological distinction between the learner and the worker

4 It enables the apprentice to be a company employee, rather than a departmental employee.

Functionally, the work is divided between supervised shop experience and systematic instruction in the trades-apprentice school. Some details of the methods which have been developed to meet modern conditions will be discussed under the following headings:

Selection
Supervised Shop Work
The Trades-Apprentice School
Incentives
Records
Graduate Apprentices.

[1] Manager, Educational Department, Westinghouse Electric & Mfg. Co.

Contributed by the Committee on Education and Training for the Industries for presentation at the Annual Meeting, New York, N. Y., December 6 to 9, 1926, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. All papers are subject to revision.

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Selection

To insure the best results, training should be started early in the life of the worker and continuously carried on in some manner throughout his employment. Boys of sixteen years of age, who have completed at least eight grades of grammar school and who have developed a desire to learn a trade, are most suitable for the training course. An investigation of the occupations of fathers of trades apprentices who have been accepted for training by the Westinghouse Electric & Manufacturing Company during the past ten years, indicates the following:

Classification	Percentage
Skilled Artisans	49
Machinists	14.7
Laborers	11.7
Executives	9.8
Farmers	8.7
Professional	6.1

Source. The boys are obtained through coöperation with the public schools, from the families of the more substantial workmen connected with the organization, and through general publicity.

Test. Each applicant is given a simple test in arithmetic. This has been found to give a satisfactory indication of the mental ability and general aptitude for the work. A typical list of questions follows:

1 What is the largest number of whole pieces 2 in. by 3 in. that can be cut from a sheet of cardboard 15 in. by 17 in.?

2 How many washers each $^5/_8$ in. in diameter can be punched from a stock sheet 3 ft. 6 in. wide by 6 ft. long?

3 A piece of copper 2 in. by 2 in. by 6 ft. long is to be drawn into a strip $^1/_2$ in. wide by $^1/_2$ in. thick. What will be the length of the strip?

4 How many "V"-shaped punchings $3^1/_2$ in. high and 1 in. wide can be cut from a sheet of steel 8 in. wide by 3 ft. 6 in. long?

5 How many 2-in. cubes can be sawed from a block 7 in. by 9 in. by 12 in.?

6 If two boys can shingle a shed in two days, how long will it take three boys to do the same job?

Also, a test is given to ascertain the physical fitness for the work desired.

Probation. The first six months of training constitute a probation period, during which time the work and attitude of the boys are checked monthly. If satisfactory, an agreement is entered into between the apprentice, his parents or guardian and the company.

Agreement. The trades-apprentice agreement outlines the responsibilities of the apprentice and the company to each other during the four-year period of the course. The main change which has been made in this agreement during the past few years was necessitated by rapidly changing rate levels during the war period.

The agreement now calls for an apprentice wage scale which is based on the going rate for certain classes of skilled labor in the plant. Instead of being inflexible, as heretofore, this rate scale is now subject to change, depending on the general wage level in the plant. By providing for a means of lowering the scale, this arrangement has made it possible to operate the course during a period of rapidly increasing rates.

The section of the agreement which provides for the arrangement is as follows:

> And the said Westinghouse Electric & Manufacturing Company in consideration of the foregoing covenants does covenant and agree that in addition to the instructions to said apprentice it will pay him for each hour of actual labor performed at a rate based on the standard wage scale as determined by the Occupation and Rates Committee. These rates are subject to change upon notice. At the date of this agreement they are as follows:
>
> 20 cents per hr. for first 1218 hr.
> 22 cents per hr. for second 1218 hr.
> 24 cents per hr. for third 1218 hr.
> 26 cents per hr. for fourth 1218 hr.
> 29 cents per hr. for fifth 1218 hr.
> 32 cents per hr. for sixth 1218 hr.
> 36 cents per hr. for seventh 1218 hr.
> 41 cents per hr. for eighth 1218 hr.

Number of Apprentices. The total number of check employees at the East Pittsburgh plant of the Westinghouse Company varies from twelve to fifteen thousand. It requires approximately three hundred apprentices, in training at all times, to supply the need for men with training of this kind. This number is determined by the nature of the work, the normal turnover of skilled workmen, the rate of growth of the plant, and the number of boys of the right caliber who apply for training.

During slack periods apprentices are not laid off. On the other hand, it is considered highly advisable that some boys be placed in training during such times, in order to insure a continuous supply of trained men.

Supervised Shop Work

Trades. Supervised training in the shop is provided for the following trades: Patternmaker, electrician, foundryman, machinist, toolmaker, and printer. Definite programs of work are laid out for each apprentice early in his course. This insures experience on a number of different jobs, work under different supervisors, and progress from the elementary to the more advanced work.

YEAR	TERM	DRAWING	SHOP PROBLEMS	SHOP MACHINERY	MONTHS	SHOP WORK
1	1	LETTERING LINES & FIGURES	ARITHMETIC	BENCH TOOLS	3	BENCH
	2	DRAWING, SYSTEMS INTERSECTIONS & DEVELOPMENT	CUTTING SPEEDS	DRILL PRESS	3	DRILL PRESS
	3	MATERIALS APPLICATION TO MANUFACTURE	ECONOMICS	LAYOUT	3	SHAPER
					3	PLANER
2	1	HAND TOOLS	PERCENTAGE	PLANER	3	PLANER
	2	WOOD WORKING TOOLS	GEAR CHANGING, THREADING INDEXING, GEAR CUTTING	LATHE	3	LATHE
					3	LATHE
	3	ELECTRICITY & MAGNETISM	MECHANICS	MILLING MACHINE	3	MILLING MACHINE
3	1	PORTABLE TOOLS	ALGEBRA	BORING MILL	3	MILLING MACHINE
	2	PATTERN MAKING, MOULDING	HEAT TREATMENT OF STEEL SLIDE RULE	AUTOMATIC MACHINES	3	BORING MILL
					3	BORING MILL
	3	MACHINE TOOLS	TRIGONOMETRY	SHAPER	3	SMALL TOOL MACHINING
4	1	GEARS & GEARING	TRIGONOMETRY	SLOTTER	3	SMALL TOOL MACHINING
	2	LAYING OUT, ASSEMBLING	MATERIALS OF CONSTRUCTION STRESSES & STRAINS	GRINDER	3	SMALL TOOL REPAIR
					3	SMALL TOOL REPAIR
	3	TOOL DESIGNING & MAKING	STRENGTH OF MATERIALS	GEAR CUTTERS	3	SMALL TOOL REPAIR

Fig. 2 Standard Apprentice-School and Shop-Training Schedule. Class Periods Two Days Each Week, 7 to 9 A.M.

Centralized Training Department. When an apprentice starts his course he is placed in a centralized training department for his first period of instruction. This department manufactures a product particularly suitable for instructional purposes. It is also provided with more and better supervisors than are the sections devoted primarily to production. During dull periods additional work is provided in this section to carry apprentices who cannot be accommodated in other manufacturing departments.

Training in this centralized department is continued for a period of from one to two years, depending on the aptitude of the apprentice and the amount of work available in the other manufacturing sections.

After completing this preliminary training, the apprentice is assigned to work in various departments where he secures additional experience under normal productive conditions.

A representative of the training department from time to time visits each apprentice in the shop to see that he is interested in his work, that the relationship between the foreman and apprentice is satisfactory, that transfer is made at the proper time and that the work of the apprentice is justly graded.

Trades-Apprentice School

Certain subjects can be more effectively taught by classroom methods than in the shop. These include mechanical drawing, sketching, general machine-shop practice, shop problems involving the application of mathematics to machine-shop processes, industrial and company history and company products and policies.

Classes. Four hours a week out of the total of forty-eight are devoted to classroom instruction. Classes are held during the first two hours of the morning, each boy attending two mornings a week. Special rooms centrally located are provided for this instruction.

Instructors. Instructors are selected from the shop, drafting rooms and engineering and commercial departments. Each spends from two to six hours a week in this work. It requires at least 130 instructor-hours each month to satisfactorily carry on the instruction for one hundred apprentices. The instructors are compensated for their time in the trades-apprentice school, the rate depending upon whether this work is outside of their regular working hours and, to some extent, upon their past experience.

The instructors attend a noon luncheon, each week, with the director of the trades-apprentice school. At this meeting problems of policy and discipline are discussed and the plans of the various instructors are coördinated.

Curriculum. The school provides a general curriculum for all apprentices, with the exception of those enrolled in the printing course. This makes it possible for the boys on each of the trades to become acquainted with other trades and with other apprentices. It also enables the work to be carried on most economically.

The subject matter has been developed by the instructors with the idea of creating a background for shop experience. Whenever possible a choice of projects or problems is allowed to take care of the individual interests of the boys. Also, work is arranged so that each apprentice can progress from one term to another as rapidly as his intelligence and efforts warrant.

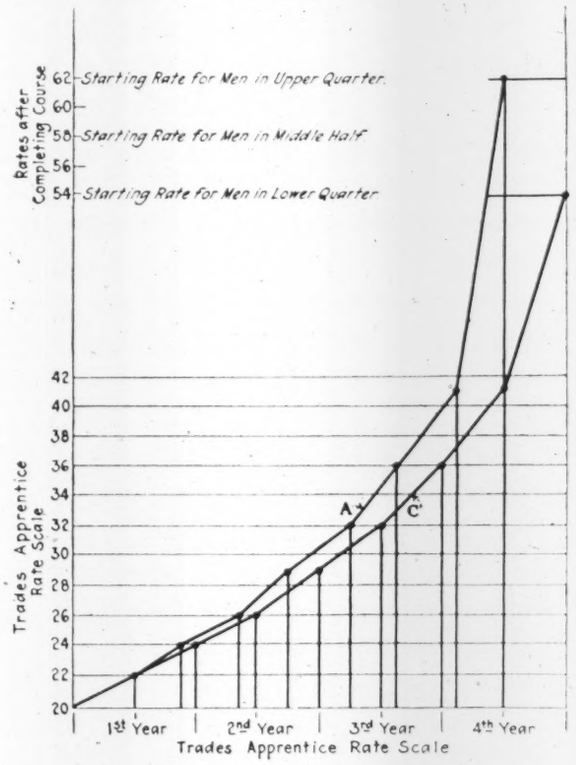

FIG. 3 TRADES-APPRENTICE RATE SCALE

(Chart showing cumulative influence of incentive grading system on the rate scale and when going on regular after completing the trades-apprentice course.)

For those who finish the twelve terms of work required of the normal apprentice before completing the course, advanced instruction is provided in such subjects as foreman training, metallurgy, personal development, and the theory of electrical and mechanical power apparatus.

The Westinghouse Technical Night School, located near the works, offers a four-year course in engineering fundamentals. Many of the apprentices avail themselves of the opportunity to broaden their technical knowledge by attending classes in this institution three evenings each week. The Westinghouse Company assists each apprentice who attends this school in the payment of his tuition. The majority of the apprentices are also similarly assisted by the communities in which they live.

INCENTIVES

One of the most important changes which has taken place in the apprenticeship relation is the establishment of constructive incentives. Some of those which have proved most effective are:

(*a*) *Wage.* An increase in rate is given every six months during the course, the rate of increase being greater during the latter years.

(*b*) *Grading.* Each apprentice is graded by the trades-apprentice committee at the end of each ten-month period for each year of his course. Those in the top quarter of their group receive an "A" grading, which carries with it a time credit of 300 hours. Those in the middle half of their group receive a "B" grading, for which a time credit of 100 hours is given. Those in the lower quarter receive a "C" grading, which carries no time credit.

In establishing this rating the shop grades are given a value of two-thirds, while the school grade is estimated at one-third. The chart used in making this grading is shown in Fig. 4.

(*c*) *Individual Attention.* The special attention of the foremen and members of the trades-apprentice staff is of great aid in stabilizing the trades-apprentice group. A staff sufficiently large

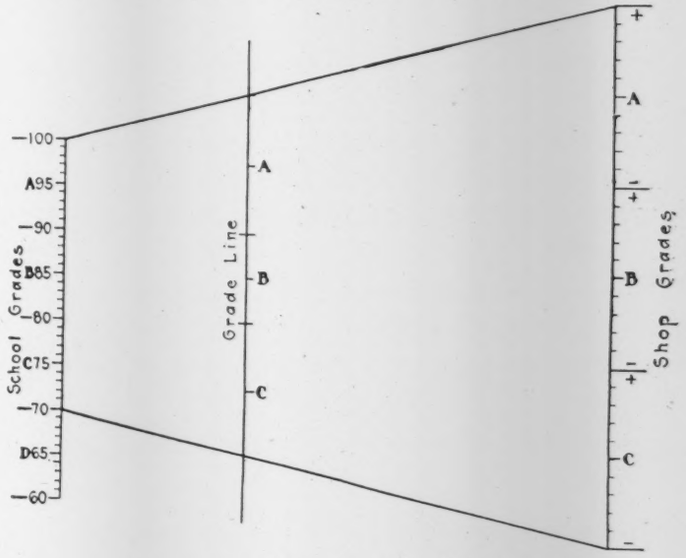

FIG. 4 TRADES-APPRENTICE GRADING CHART

(Connect Shop and School Grades with a straight edge and read yearly grade on Grade Line.)

to maintain this personal contact must be provided for success in the work.

(*d*) *Preference in Work.* Apprentices who show marked ability, or who are unusually diligent in their work, are recognized by being shown some preference in the kind of work on which they are placed and the length of time which they spend on each kind of work.

(*e*) *Experience Outside of Plant.* Coöperative relations are maintained with the subsidiary plants of the company and with certain outside organizations.

Apprentices are given outside assignments from time to time as a reward for meritorious work. This provides some of the same benefits which were formerly received by the journeyman who started out to broaden his experience by securing employment in various plants.

(*f*) *Diploma.* Upon the completion of the course the apprentice is granted a diploma specifying his qualifications for the trades and signed by the proper officials of the company.

(*g*) *Publicity.* At the time of completing his course some information regarding the apprentice's training and future work is placed in his home-town paper and also in the shop newspaper.

(*h*) *Journeyman Starting Rate.* The starting rate of the graduate apprentice is determined by his record he makes during the course.

(*i*) *Follow-Up After Graduation.* Opportunities are provided for advancement to work of responsibility after completing the course. These opportunities are either along the line of the trade followed or in the field of supervision.

Each graduate apprentice is checked by the works-manager's office every six months during the first two years after completing the course. This insures that his work and wage are correctly assigned.

The careful placement and follow-up of graduate apprentices has proved to be one of the greatest aids in attracting the right type of boy to the course.

(*j*) *Scholarships.* As a war memorial the company provides a fund of $8000 each year to assist employees or sons of employees in securing a college education. Awards are made on the basis of a competitive examination, which is open to trades apprentices as well as to other employees of the company.

(*k*) *Prizes.* The works executive committee, veterans' association, clerks association and foreman's association each year contribute prizes for meritorious work. These are awarded at the annual trades-apprentice dinner which is held under the auspices of the trades-apprentice alumni association. In this manner, the boys on each year of the apprentice course who have made the greatest progress during the year are recognized and, at the same time, the interest of the supervisory force in apprentice activities is aroused.

RECORDS

Grades are to the student what wages are to the regular workman. The trades apprentice is both student and workman. Careful grading is the basis for the application of incentives and is very essential to the most successful carrying on of the work.

A complete record of each apprentice is maintained throughout his course. The shop supervisor grades each apprentice once every month. The points considered are: performance, conduct, dependability, intelligence, attitude, and physical fitness for the work. In addition to this grading, a report is received once each term from the trades-apprentice school. A time record also is kept as a basis for making transfer and changes in rate and checking regularity in attendance.

Each apprentice turns in a report once each year covering the work he has done on the course up to that time, and including any changes in the program which he would like to have carried out to more nearly meet his needs.

The trades-apprentice committee reviews the records of each apprentice once each year to determine the quarter of his group in which he should be classified.

GRADUATE APPRENTICES

The certificate awarded to the apprentice, upon the completion of his course, is presented at a meeting which is attended by the superintendent for whom he will work, representatives of the training department and the graduate apprentice. This meeting affords an opportunity to review briefly the experience which the graduate has had and to talk over with him plans for the future. It also gives the superintendent information which can be used in placing the graduate to the best advantage.

The graduate-apprentice association maintains a record of those who have completed the training; conducts several meetings of a social or educational nature each year; assists in developing morale among apprentices and graduate apprentices, and in establishing a favorable public opinion toward the skilled worker in the community.

Approximately 50 per cent of the apprentices who have completed their courses since 1908 are still in the employ of the Westinghouse Company. Of these, 40 per cent are in supervisory work, a few have gone into office positions, while the remainder are following the trades for which they were trained.

CONCLUSIONS

There is an increasing need in our industries for more and better trained men. Trades apprenticeship is more nearly in accord with the interests of the better class of boys than regular employment on specialized jobs. This was clearly demonstrated during one year of the war period when the demand for labor was urgent. The turnover on the trades-apprentice course was 22 per cent as compared with nearly 400 per cent for boys of the same age on miscellaneous jobs.

Apprentice training also meets the needs of management. By maintaining close contact with apprentices, teachers, parents, graduates and prospective apprentices, a program can be carried out on a sound economic basis under present conditions.

The engineer has always been interested in developing materials and power and using them to the best advantage. Today he recognizes the need for trained men and to this problem he is applying his accustomed analytical ability and courage.

Educational Training for Industry

By MATTHEW WOLL,[1] WASHINGTON, D. C.

ORGANIZED labor's interest in education for industry is rooted in one of its most fundamental purposes—the conservation of craftsmanship. It is this idea which underlies the whole structure of American unionism. Bricklayers, machinists, electricians, printing pressmen are on a trade basis; it is their common craft interest that binds them together.

It follows, then, that craft skill is a very important thing with these workmen. Creative expression in work is a strong motive with all men who do work of any kind, be they artists, business men, or the men who run our machines. A chance to use one's intelligence to develop an ever-greater excellence of workmanship is, in the long run, the thing which redeems work from pure drudgery and makes it worthy of human effort. The workmen themselves realize this. They realize it in a more compelling way than the business men, managers, and directors of their industries, whose work has the intellectual stimulus and variety of executive activity. In the workmen's nearness to drudgery, the need for creative expression is very urgent.

To fill this need the men naturally turn to their union, since it is the embodiment of their common craft interest. The union, which is the custodian of trade skill and past experiences, becomes their means of contact with an agency which makes possible sustained development of craftsmanship. Through magazine articles, lectures by experts, and workers' education classes the unions are keeping their members abreast of the latest craft developments, new inventions and trade processes, information on industrial problems, which will enable them to apply their minds effectively to their jobs. Further than this, the union maintains standards of craftsmanship for the admission of new members. It also takes the responsibility of disciplining those who do not maintain a high quality of workmanship. This goes even to the point of expelling members who do not live up to union standards. Thus it has come about that the union sets and holds standards of craftsmanship in an industry. It is the only standard-setting agency in the industrial field which exercises this function.

Trade education is that which makes skilled craftsmanship possible. In the complicated machine processes of our modern industries it is the sine qua non of creative expression for the workman. The boy who wants to be a carpenter, machinist, printer, needs first a technical knowledge of the trade. This should include the study of mathematics, architecture, physics, English, and such other subjects as are the background of a true understanding and mastery of his craft. It includes also a thorough knowledge of trade processes. Secondly, the apprentice must have trade experience under expert guidance. And thirdly, he must know the economic and business problems of his trade. The boy who is entering less highly skilled work needs less technical education and trade experience, but knowledge of his trade problems is just as essential. For without this knowledge he is handicapped in taking an understanding part in developing trade efficiency or seeing the relation of his particular job to the whole industry and appreciating the significance of his own accomplishments.

Trade Education in Public Schools Should Be Under Joint Control of Employers, Unions, and Schools

This trade education when carried on through public schools should be under the joint control of employers, the unions, and the public school. Each group has its special contribution to make: the employers as the group controlling business decisions have information about trade problems, access to equipment, and opportunities to give apprentices practical experience; the unions set the standards in craftsmanship, have intimate knowledge of each operation, and can furnish expert supervision and counsel; the schools have the machinery of instruction and educational experience. No one group without the others could give a fully rounded education.

When the worker has had this first preparation, he is ready for the second part of his education: that which goes on continually through his daily work. To the craftsman as to the artist, the professional man, or the business man the development of skill in work grows out of the work itself. It is a process by which the worker masters the job details, gains understanding of its problems, and finally reaches the point where he turns his energies to improving the job itself. It is this latter—the improvement of the job—which gives him scope for continued self-education and development, for creative expression in work.

To provide conditions such that this creative expression through job improvement can go on and can be the means for increasing industrial efficiency is by no means an impossible task. The average workman develops a technical knowledge of his job and thinks of ways his work might be better done, waste eliminated, and time and energy saved. Because of his intimate contact with job details and his specialized knowledge he can suggest improvements which are outside the experience of management and so make a specialized contribution. When he has no channels through which to voice his ideas, they are lost to the industry. But if the means can be found to make these ideas available for practical use, a working force of men intent upon increasing efficiency can be developed and a chance for all to find creative expression in their work will be provided.

Coöperation Between Management and Men to Increase Production Efficiency

This means must come through coöperation between management and men to increase production efficiency. The welfare of the industry is a real interest with the workers. Their livelihood depends upon it, and the means for increasing their wages must come from its prosperity and efficiency. Therefore it can well be the basis of coöperation between the two groups, bringing them together in the common work of industrial improvement. But in order that the workers may join with management in wholehearted coöperation, certain conditions are necessary: they must have confidence and they must feel responsible for their share in the common enterprise; they must know that management will give them the chance to put their ideas into practice when they are worth while, since management is the controlling force. Especially they must know that when profits result from their efforts they will receive their full share. Only under such conditions can the workers' full mental energy be liberated for their work.

This condition can be brought about through the trade union. The union is the agency for mobilizing the human factor in industry. Through it progress in human engineering can keep pace with progress in the mechanical sciences. It is the organization which has the men's complete confidence; it calls out their initiative, enables them to take responsibility, and to discipline their own members; it provides the machinery necessary for contact between management and the individual men. And above all it trains leaders—men with the initiative and intelligence that come from working out their own problems; and with the understanding of industry and the knowledge of human nature that come from guiding their fellows through the human difficulties that continually arise in their daily work. The unions are ready to coöperate with management in the task of raising industry to the highest possible degree of efficiency.

In many industries trade unionists are already coöperating, and both together have worked out a scheme by which the individual worker may be effective in increasing production efficiency and thus find creative expression and continued education in work. In certain papermaking plants the men have means for keeping check on the quality of the paper they produce and are continually working under the guidance of their union leaders to improve quality and save waste. In the printing industry the Pressmen's Union maintains three experts who keep constant watch on the quality of all

[1] President International Photo-Engravers Union.

Contributed by the Committee on Education and Training for the Industries for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of The American Society of Mechanical Engineers. All papers are subject to revision.

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work done by union men, and when poor work is found, visit the plant concerned, examine conditions thoroughly until the cause is discovered, and show the men how to avoid it. The Cleveland garment unions carry out this job improvement through joint committees to study the problems of standard-setting for the trade. In the repair shops of the B. & O. Railroad, joint shop committees of management and union representatives meet every two weeks to discuss production efficiency. To these meetings the individual workmen submit suggestions for improvements in machinery, tools, methods of work. These suggestions are passed upon by the committees and if approved are adopted into the shop system. In the last three years over fourteen thousand suggestions have been given of which eighty per cent were accepted. Many of these were inventions made by the men themselves. Many other examples of union-management coöperation could be cited where the men, through their unions, are making a definite contribution to the industry and are finding creative expression and education in their work.

In my own trade, photo-engraving, where processes are changing rapidly to keep pace with scientific progress and inventions, the workmen depend upon the union to provide them with the necessary information to equip them for new processes.

This chance for intellectual expression in work is the logical next step in industrial progress. It provides for continued improvement in efficiency without making the individual worker a mere cog in the industrial machine; it makes full use of the human qualities that are now so often wasted, and at the same time gives the worker a chance to employ creative expression in his work. Such a condition is a fitting goal for education in modern industry. As L. P. Jacks has said:

> Education is the process of training the industry of man in its manifold varieties and its organized totality to the highest pitch it is capable of attaining. Such education will have its roots in the actual labor of mankind and will return into that labor to endow it with higher qualities and more valuable aims.

The Tangent Method of Analysis for Indicator Cards of Internal-Combustion Engines

By P. H. SCHWEITZER,[1] STATE COLLEGE, PA.

This paper deals with a new method which has been developed for analyzing indicator diagrams. The method essentially consists of drawing tangents to the pressure curve and a subsequent graphical construction gives the direction of the heat flow at any point of the expansion or compression line. The tangent method of analysis is simple in execution, is sufficiently accurate and has been of distinct assistance in testing internal combustion engines.

INDICATOR diagrams have not been used nearly as extensively for studying the performance of internal-combustion engines as for steam engines. An indicator diagram is a complete record of the changes the working medium is subjected to within the cylinder, and subsequently should offer an ideal means for judging the performance.

In an internal-combustion engine the changes taking place in the cylinder include the admission and mixing of fuel and air, the production of heat and its conversion into work, and the removal of the combustion products. Each operation has a bearing on the performance, and any improvement of an engine requires an intelligent knowledge of the engine process.

The lack of general use of indicator diagrams in connection with internal-combustion engines may be explained in two ways:

1 The indicators used for steam engines are not well suited for high-speed internal-combustion engines and usually do not give cards of sufficient accuracy.

2 No easy means are widely known for interpreting the indicator cards and obtaining the information desired.

Distinct progress has been made in both directions in recent years. Indicators of the pencil type have been perfected to the extent that they can be safely used for engines up to 300 r.p.m. Optical indicators, being free from most of the defects of mechanical indicators, give useful service in research work. Also, there have been developed recently various types of balanced or "point to point" indicators which seem to combine the advantages of the pencil and optical indicators by eliminating the inertia effects while maintaining the mechanical features and sturdiness of the pencil-type instruments.

Even the best indicator diagram is of no value if one does not know how to interpret the record. Indicator diagrams of a given type of engines, as for instance, air-injection Diesels, look so much alike that a mere inspection of a card will reveal nothing but the grossest deviations from the standard cycle. Therefore internal-combustion-engine diagrams are seldom used for more than determining the maximum gas pressures and for rough comparisons.

Exponential Analysis

Heat Flow Within the Cylinder. An indicator diagram shows only the pressure changes in an engine cylinder; it fails to show explicitly where heat is absorbed and where heat is given up by the cylinder contents. This is a very important point, particularly in an internal-combustion engine where both the production of heat and its conversion into mechanical work are performed within the cylinder. In studying the performance of an engine, knowledge of the *heat movement* is essential.

Güldner's Method of Analysis. The exponential analysis was early recognized as an excellent means to get the story of the heat movement inside of the engine. Güldner[2] recommended that such an analysis be made whenever a thorough examination of the engine indicator cards was required.

Since the exponent in the equation for the adiabatic change is equal to $k = c_p/c_v$, we know at once that, if an actual pressure-volume expansion line for any given gas shows an exponent n different from k for this gas, the change was not adiabatic. If in such a case $n>k$, heat has been withdrawn during the change, while, if $n<k$, heat must have been supplied. On the other hand, the opposite relations hold for the compression line.

In order to determine the variation of n during an expansion or compression stroke, he recommended the method of dividing the diagram into sufficient (five or ten) sections (Fig. 1) and then calculating the exponent of each curved part lying between two ordinates x and y by the formula

$$n = \frac{\log p_x - \log p_y}{\log v_y - \log v_x}$$

For best results, Güldner recommended that the step-by-step analysis be made on a diagram enlarged 5 to 10 times. In spite of the emphasis laid upon such a thorough examination of the engine indicator cards, the suggested method was too cumbersome to become very popular.

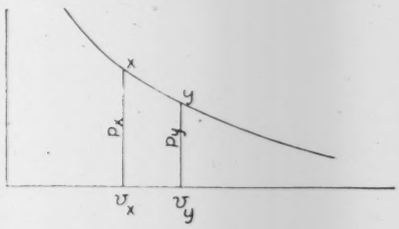

Fig. 1 Section of a Pressure Curve

Clayton's Logarithmic Diagram. J. Paul Clayton[3] introduced the logarithmic plotting of the indicator cards, which offered a more convenient way to get information regarding the heat movement.

The absolute pressures are plotted against the absolute volumes to any scale on logarithmic cross-section paper. If the points corresponding to the compression or expansion lines lie on a straight line the trigonometrical tangent of the slope of that line (to scale) indicates the exponent "n" for the respective period. If the points do not lie on a straight line, the slope of the tangents drawn to various points of the curve are indicative of the respective n's.

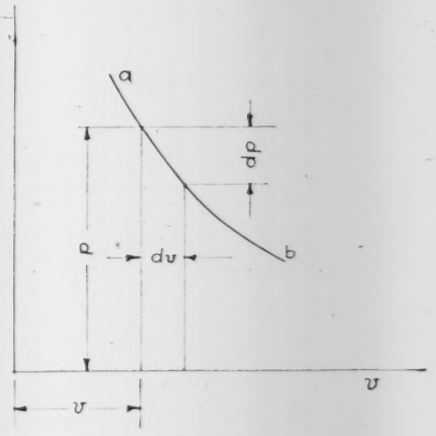

Fig. 2 Change of State on a p-v Diagram

This method has been used extensively and has given very useful results.

Tangent Method of Analysis. In this paper another method of analyzing indicator diagrams will be presented which, though simple, is not generally known.

The construction is shown in Fig. 3. It has the advantage of giving results directly with little effort and sufficient accuracy. A proof of the construction will be given later in this paper.

Thermodynamics of Indicator Diagrams

Analysis of the Heat Flow. In Fig. 2 the line *ab* represents the pressures corresponding to volumes of a definite amount, say, one

[1] Associate Professor of Engineering Research, Pennsylvania State College.

[2] Güldner-Diederichs, Internal-Combustion Engines, 1910, p. 573.

Contributed by the Oil and Gas Power Division for presentation at the Annual Meeting, New York, N. Y., December 6 to 9, 1926, of The American Society of Mechanical Engineers. The paper forms part of a forthcoming bulletin (No. 35) of the Engineering Experiment Station, The Pennsylvania State College. All papers are subject to revision.

[3] A New Analysis of the Cylinder Performance of Reciprocating Engines, University of Illinois Bulletin No. 58, 1912.

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pound, of gas or gas mixture. During this change a certain amount of heat has been absorbed or given up by the gas.

The first law of thermodynamics as expressed in a conventional form is for perfect gases

$$dQ = c_v dT + A p dv \quad [1]$$

where c_v is the specific heat for constant volume and A the reciprocal of the mechanical equivalent of heat. dT being a total differential can be expressed as

$$dT = \frac{\partial T}{\partial v} dv + \frac{\partial T}{\partial p} dp$$

which with $pv = RT$ gives

$$dT = \frac{p}{R} dv + \frac{v}{R} dp \quad [2]$$

Substituting Equation [2] in Equation [1],

$$dQ = \left(\frac{c_v}{R} + A \right) p dv + \frac{c_v}{R} v dp \quad [3]$$

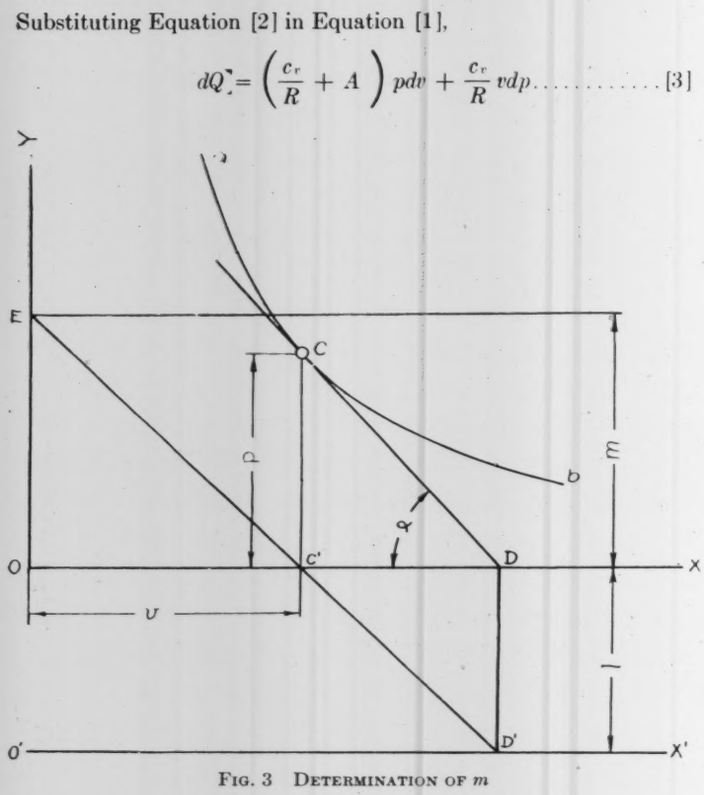

FIG. 3 DETERMINATION OF m

Considering that for all perfect gases $c_p - c_v = AR$,

$$dQ = \left(\frac{c_v}{R} + \frac{c_p - c_v}{R} \right) p dv + \frac{c_v}{R} v dp$$

or

$$dQ = \frac{c_p}{R} p dv + \frac{c_v}{R} v dp \quad [4]$$

This gives the amount of heat absorbed by the gas during a differential change which increased its volume from v to $v + dv$. If dQ turns out to be negative, it indicates that heat was rejected rather than absorbed during the respective period.

In reference to indicator diagrams it is of particular interest to know whether heat is absorbed or given up at a certain point corresponding to a certain position of the piston in the cylinder.

Dividing both sides of Equation [4] by dv, we obtain

$$\frac{dQ}{dv} = p \frac{c_v}{R} \left(\frac{c_p}{c_v} + \frac{v}{p} \frac{dp}{dv} \right) \quad [5]$$

Since $p \frac{c_v}{R}$ is positive in any case,

$$\frac{dQ}{dv} \gtreqless 0 \text{ if } \frac{c_p}{c_v} \gtreqless - \frac{v}{p} \frac{dp}{dv} \quad [6]$$

Considering that dv is positive during expansion and negative during compression, the conclusions to be drawn from this analysis can be summarized as follows:

The direction of heat flow at any point of an expansion or compression line is determined by the relative amount of the two quantities $\frac{c_p}{c_v}$ and $\frac{vdp}{pdv}$. Denoting $\frac{c_p}{c_v} = k$, and $-\frac{vdp}{pdv} = m$, the rule can be stated as follows:

During expansion { introduction / rejection } of heat takes place if { $m < k$ / $m > k$ }

During compression { introduction / rejection } of heat takes place if { $m > k$ / $m < k$ }

To arrive at this conclusion nothing has been assumed except that we are dealing with a substance which follows the law of gases, $pv = RT$.

Graphical Determination of the Heat Flow. In the above analysis the nature of the change as represented in Fig. 2 is not limited in any sense, and the line ab does not necessarily represent a so-called polytropical line. It was shown that in order to determine the direction of heat flow at any point C, $m = -\frac{vdp}{pdv}$ has to be evaluated and compared with $k = \frac{c_p}{c_v}$. It is very fortunate that on the indicator diagram this can be done by an easy graphical method.

In Fig. 3, ab represents an expansion curve. OX is the zero absolute pressure and OY the zero volume line. Below and parallel to OX at a unit distance, say, one inch, the line $O'X'$ is drawn. The line CD is tangent to the curve a-b at C. Projecting C to OX and D to $O'X'$ points C' and D' are determined. Connecting C' and D', the section OE on the OY-axis represents the value of m at point C. If the distance DD' is one inch, the distance OE scaled in inches will give the value of m.

The proof of the construction is as follows:

In Fig. 3, from the similar triangles,

$$\frac{OE}{OC'} = \frac{DD'}{C'D}$$

$$OE = \frac{OC' \times DD'}{C'D}$$

Since $OC' = v$, $DD' = -1$ and $C'D = \frac{p}{\tan \alpha}$, we may write

$$OE = -\frac{v}{p} \tan \alpha$$

and substituting $\tan \alpha = \frac{dp}{dv}$

$$OE = -\frac{v}{p} \frac{dp}{dv}$$

which is exactly the definition of m.

Thus, in order to determine the heat movement from the p-v diagram of a perfect gas, all we have to do is to construct n in the manner just described and compare it with k. Then

During expansion { introduction / rejection } of heat takes place if { $m < k$ / $m > k$ }

During compression { introduction / rejection } of heat takes place if { $m > k$ / $m < k$ }

APPLICATION OF THE HEAT-FLOW ANALYSIS TO INDICATOR DIAGRAMS

Working Medium in Internal-Combustion Engines. The working medium in the cylinder of an internal-combustion engine before combustion is a mixture of air with fuel gas or fuel vapor. The air is always preponderant in the mixture, the weight proportion being from 1 : 1 to 7 : 1 with gaseous fuels and from 8 : 1 to 30 : 1 with liquid fuels.

The cylinder content both before and after combustion consists largely of diatomic gases and contains comparatively little vapor. Since the deviations are slight, it is legitimate and customary, for all practical purposes, to treat the cylinder contents of internal-

combustion engines as perfect gases and apply the gaseous law $pv = RT$ to them without any correction.

Analyzing Indicator Diagrams. Since the working fluid in an internal-combustion engine is substantially gas and the indicator diagram gives a record of the variation of pressures in relation with the volumes, the method described is applicable for the determination of the heat flow in the working cylinder of the engine during the various stages of the engine cycle and also for air and gas compressors.

It has been pointed out that the method strictly holds only for perfect gases. The deviation caused by the imperfectness of the gas has been investigated and found to be well within the experimental errors in case of internal-combustion engines and air compressors.

Indicator Diagrams and "p-v" Diagrams. In applying the heat flow analysis to indicator diagrams, conditions must be identical with those for which the method has been developed.

An indicator diagram is often regarded as a p-v diagram, but strictly it is not.

In order to convert an indicator diagram into a proper p-v diagram, (1) the v-axis has to be drawn below the atmospheric pressure line at a distance, equal to the atmospheric pressure, to scale, and (2) the p-axis has to be drawn from the zero displacement line at a distance which is equal to the clearance volume of the working cylinder, to scale.

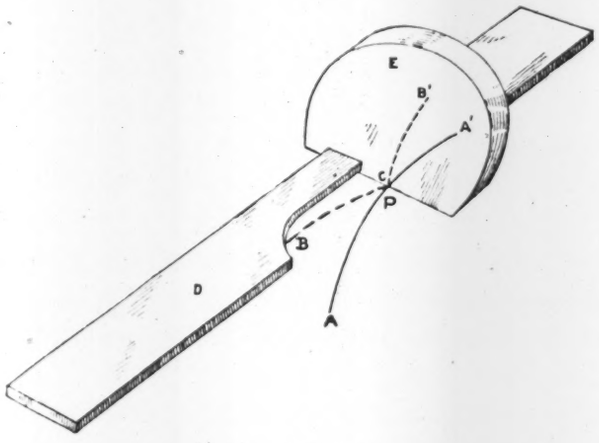

FIG. 4 MIRROR RULE

An indicator diagram so treated really represents a p-v diagram proper, if no change of weight of the working medium occurs during the cycle it represents. This requirement is very essential, because the cylinder total volumes are not proportional to the specific volumes of the gas unless the weight of the gas is constant. If the weight W of the working medium varies during the change, a diagram having total volumes $V = Wv$ for abscissas cannot be considered a p-v diagram proper.

Variation of the Cylinder Content. An indicator diagram represents the pressure variation in a cylinder, the gas content of which generally varies, due to leakage in the weight of the gas.

It follows, then, that care must be exercised in applying the heat-flow analysis, which strictly holds only for true p-v diagrams. It is evident that during periods when valves are open, no heat-flow analysis can be made with the present method. This, however, does not exclude the application of the analysis for periods of the cycle when the gas content is sensibly constant. Condensation or evaporation is seldom of such a magnitude as to vary the weight of the gas appreciably. During periods when all valves are closed and there is no appreciable leakage, the corresponding parts of the indicator diagram can be regarded as true p-v diagrams and analyzed as such. For compression and expansion lines the analysis gives results that can be interpreted in useful terms.

If the heat-flow analysis is applied to periods of admission, injection, or exhaust, it becomes meaningless and the usual interpretation of the results would lead to wrong conclusions.

THE MIRROR RULE

Drawing Tangents. The accuracy of drawing tangents to a general curve can be increased by the use of the simple instrument shown in Fig. 4. It consists of a rule D to which a silver-plated mirror-like polished metal block E is attached at right angles. The point C, which is in alignment with the edge of the scale, is marked on the edge of the block. The device is placed on the paper with the point C in contact with the point P on the curve to which it is desired to draw a tangent. When the image $A'C$ appears as a continuation of the original curve PA, the edge of the rule is tangent to the curve at P. A line drawn at the edge of the rule in such position will be a tangent line at point P. If the scale is not tangent, the reflection of the curve will be somewhat as shown by the broken line $B'C$.

ANALYSIS OF INDICATOR DIAGRAMS OF INTERNAL-COMBUSTION ENGINES

Compression and Expansion not Adiabatic. The heat movement in the cylinder of an internal combustion engine is rather complex. In theory it is usually assumed that the compression and expansion lines are adiabatics. In fact this is never the case, for a continuous interchange of heat takes place between walls and cylinder contents.

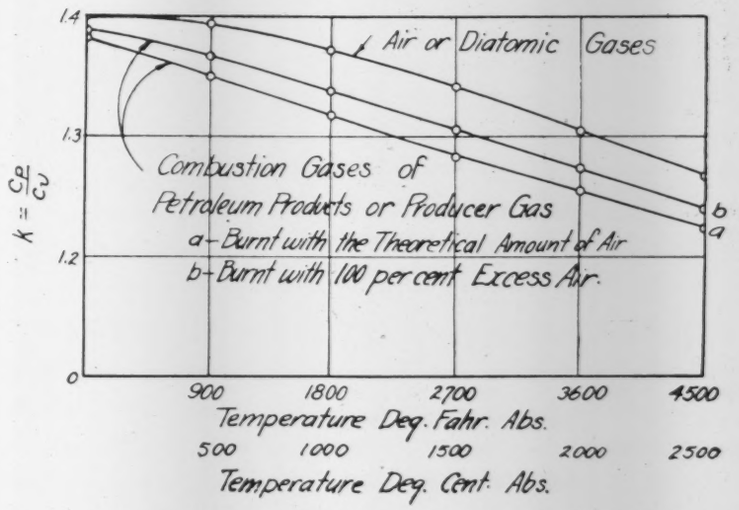

FIG. 5 ADIABATIC EXPONENT k FOR DIATOMIC GASES AND COMBUSTION PRODUCTS

Neither is the combustion limited to the period of injection or ignition.

Examination of the actual processes reveals the fact that the combustion continues long after the ignition and fuel injection are over. In many engines the combustion is not even finished when the exhaust valve opens.

Bearing in mind the influence of the delayed burning and the wall effect, we cannot expect the gases to expand adiabatically. One should rather expect the heat flow to be decidedly positive in the early part of the stroke and slightly negative at the end, unless afterburning is present.

According to the variable influences of the ignition, combustion cooling, etc., the heat movement of different engines will be different and characteristic of the particular type of engine.

Construction of the "m"-Curve. The heat flow analysis described gives a simple means for determining the direction of the heat flow for the expansion and compression lines of indicator diagrams. To get a picture of the whole heat movement, divide the stroke into, say, 10 parts and construct the m for each intersection. Also draw the $\frac{c_p}{c_v} = k$-line and compare the m-line with the k-line. During compression, if the m-line is above the k-line it means heat introduction, and if the m-line is below the k-line it means heat rejection by the gas. If, during expansion, the m-line is below the k-line it means heat introduction, and if above, heat lost by the gas.

Hence, by determining the value of m at several points and combining them into an m-curve, a true picture is obtained of the heat movement during the part of the cycle when the valves are closed. By inspecting the m-curves various conclusions as to the combustion velocity, afterburning, cooling, etc., can be drawn which are characteristic of the particular engine.

Temperature Variations of the Cylinder Content. The m-curve, incidentally, gives information relative to the temperature variations of the working medium within the cylinder.

For a perfect gas, $T = \frac{pv}{R}$

so

$$dT = \frac{\delta T}{\delta p}\,dp + \frac{\delta T}{\delta v}\,dv = \frac{v}{R}\,dp + \frac{p}{R}\,dv \quad \ldots\ldots [7]$$

The temperature of the gas is maximum (or minimum) when $dT = 0$, i.e.,

$$\frac{v}{R}\,dp + \frac{p}{R}\,dv = 0 \quad \ldots\ldots [8]$$

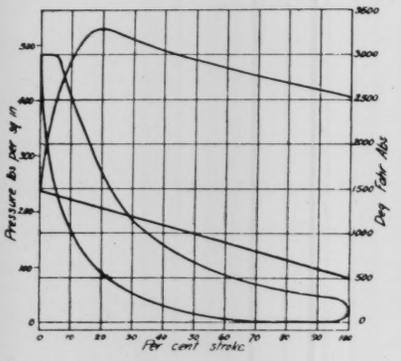

FIG. 6 TEMPERATURE DIAGRAM OF A DIESEL ENGINE

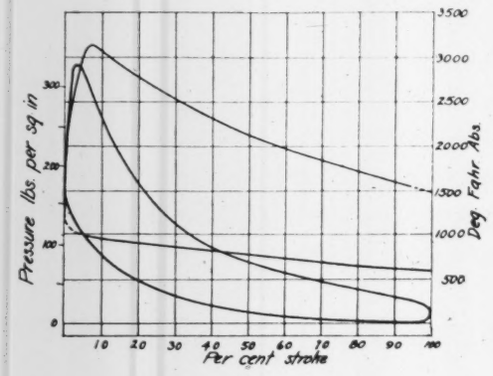

FIG. 7 TEMPERATURE DIAGRAM OF A GAS ENGINE

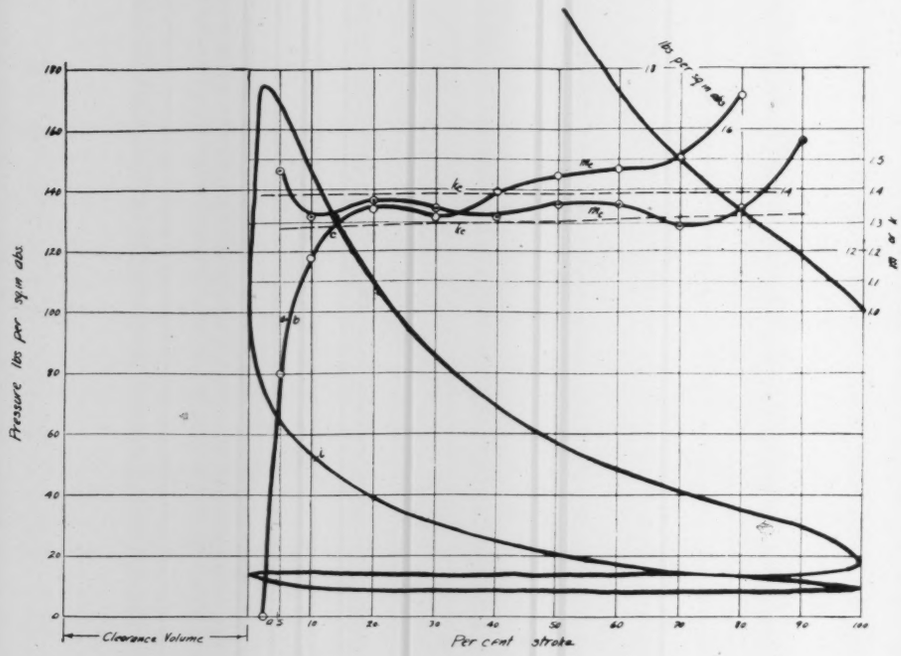

FIG. 8 STUDY OF AN ACTUAL DIAGRAM

or

$$-\frac{v}{p}\,\frac{dp}{dv} = 1 \quad \ldots\ldots [9]$$

The left side of Eq. [9] has already been designated by the symbol m. Consequently, $m = 1$ is an indication of the fact that the gas temperature is a maximum or a minimum at this moment in the cylinder.

The maximum temperature in an internal-combustion engine cycle generally occurs shortly after the head dead center of the expansion stroke. The corresponding piston displacement can be easily found. It is the intersection of the m-curve with the $y = 1$ line. At this point the gas has peak temperature, before which the temperature is continuously rising and after which it is continuously falling. It is obvious that the more rapid the ignition, the more quickly will the peak temperature be reached. The crank angle between the head dead center and the position of peak temperature is characteristic of the ignition speed and of the particular engine.

Method of Drawing the "k"-Lines. In calculations with respect to internal-combustion engines, $k = \frac{c_p}{c_v}$ is usually taken as 1.4 for both air and combustion gases. However, this approximation is not close enough for most purposes. Due to the increase of the specific heats with the temperature, k appreciably decreases. Furthermore, k is smaller for combustion gases than it is for air. In examining the m-curves, the true k's should always be used for comparison.

In Fig. 5 the k's are plotted for temperatures 0–4500 deg. fahr., or 0–2500 deg. cent. The upper curve is for air or diatomic gases, and the lower is for pure combustion gases of producer gas and petroleum products. Between the two, a third curve is drawn, representing the k's for combustion gases of petroleum products burned with 100 per cent excess air, as is usually the case with Diesel engines and other injection oil engines. Gas engines usually give best results with about 50 per cent excess air, and carburetor engines with about the theoretical amount. The curves for combustion gases with a small amount of excess air run so close to the k's of the pure combustion gases that the latter can be substituted for them.

In order to draw the k-lines on the indicator diagrams, the temperatures of the cycle have to be known. Fig. 6 shows the temperature variation for a gas engine running on illuminating gas and Fig. 7 the same for an air-injection Diesel engine.

It will be noted that the lines on the diagrams differ but little from straight lines between the beginning and end of compression and also between the points of maximum temperature and opening of the exhaust valve. The k-lines for various temperatures are also approximately straight. Hence the k's of the indicator diagrams can be closely approximated by drawing straight lines between known points.

Study of an Actual Diagram. Fig. 8 is a reproduction of an actual gas-engine diagram. The spring scale is 1 in. = 60 lb. per sq. in. The compression ratio of the engine was given as 4.43 to 1 and the speed as 336.8 r.p.m.

The lower part of the compression line has also been drawn to a ten times' larger scale, 1 in. = 6 lb. per sq. in., in order to obtain less obtuse intersections for this part of the diagram. It can be shown that if the angle between the tangent and the volume axis is less than 10 deg. or more than 80 deg., the error is likely to exceed 10 per cent. Therefore, generally not much can be gained by extending the m-curve over that part of the compression line. However, drawing the ordinates of the compression line to a larger scale, we can increase the respective angles and at the same time the accuracy of the construction. The same results can be obtained by employing weak-spring diagrams for the analysis of the lower part of the compression line.

In order to draw the m-curves it is advisable to divide the stroke into 10 equal parts. Generally it is sufficient to determine the m at every 10 per cent stroke of both the expansion and compression line. Sometimes a subdivision of the first section into two is advisable.

Location of the Axis. Before starting the graphical construction the axis must be drawn. The horizontal axis or the zero-pressure line has been drawn 14.5 lb. below the atmospheric line. In order

to draw the vertical axis or the zero-volume line, the compression ratio has to be considered.[4] Since the compression ratio for this card is 4.43 and the length of the card 3.34 in., the vertical axis is drawn at a distance of $3.34/4.43 - 1 = 0.954$ in. from the right end of the card. This distance corresponds to the clearance volume of the cylinder to the scale of the indicator card.

Construction of the "m"-Curves. After the location of the axis, the construction of the m-curves can be started. At any suitable distance below the zero-pressure line the —1 line is drawn and at the same distance above the zero-pressure line the + 1 line. It is advisable to draw at the same time the 1.1, 1.2, 1.3, 1.4, and 1.5 lines, which will serve as a scale for the m-curves. Then at each point the m's are constructed, as has been described. The sequence of the points is immaterial.

The m's for the expansion lines have been determined for points corresponding to 5, 10, 20, 30, 40, 50, 60, 70, and 80 per cent stroke. At 90 per cent stroke the exhaust valve is already open, so the construction of the m is meaningless at that point. An additional point can be obtained by projecting the maximum pressure point to the zero-pressure line.

The m's for the compression line are constructed in the same manner for points corresponding to 5, 10, 20, 30, 40, and 50 per cent stroke. At 60, 70, 80, and 90 per cent stroke the upper curve has been used for the construction which is otherwise identical. However, the tangents drawn to the upper curve which has ten times larger ordinates, gave more distinct intersections with the zero-pressure line than the flat curve which forms the lower part of the compression line. For identification, the m's for the compression line have been marked by points with a dot in them. Then a smooth curve through the respective points was drawn.

The shape of the two curves m_e and m_c gives a general idea of the combustion, ignition, and cooling characteristics of the engine. In order to make the analysis more exact and specific, it is always advisable to draw also the k-lines, as already described. The k-lines are shown dotted in the figure.

Interpretation of the Results. Having m_e, m_c, k_e, and k_c, the interpretation of the results involves the following steps. In examining the expansion m-curve, the points a, b, and c deserve particular attention. Point a indicates the maximum pressure, point b the maximum temperature and point c the maximum heat content. Point a is the intersection of m_e with the zero-pressure line. Point b is the intersection of m_e with the 1 line. Point c is the intersection of m_e with the k_e line. Between a and b the gas loses pressure but gains in temperature. Between b and c both pressure and temperature are decreasing, but the gas still is gaining heat on account of the retarded combustion. The burning which takes place after attaining maximum temperature is often called "afterburning." This use of the term is somewhat misleading, because it is evident that the combustion *never* can be completed at the time the maximum temperature is reached.

The elapsed time between points b and c will be called *combustion lag*. Similarly, the time between points a and b will be called *temperature lag*, and the time between the ignition point i and a, *pressure lag*. In Diesel-type engines the ignition point virtually coincides with the head dead center.

The pressure lag, temperature lag, and combustion lag are mainly determined by the combustion velocity. If the expansion m-curve runs below the k-line during the entire stroke, no c-point will exist, which indicates that the combustion extends over the entire period of the expansion stroke and is not even completed at the end of the stroke. Afterburning of this type can often be detected by a smoky or colored exhaust or flames.

By measuring the respective distances from the head dead center, we find that the maximum pressure occurs at 2.5 per cent, maximum temperature at 6.7 per cent, and maximum heat content at 13.3 per cent stroke. With a 4.75 connecting-rod ratio the corresponding crank angles are 16.7, 27.7 and 39.5 deg. The ignition point is given as 35 deg. before dead center. Tabulating all characteristic points

	i	a	b	c
Per cent stroke	−10.7	2.5	6.7	13.3
Deg. crank angle	−35.0	16.7	27.7	39.5

from which the pressure lag figures as $16.7 - (-35) = 51.7$ deg., the temperature lag $27.7 - 16.7 = 11$ deg., and the combustion lag $39.5 - 27.7 = 11.8$ deg.

Knowing the engine speed, the respective lags can be expressed in seconds.

$$\text{Pressure lag} = \frac{51.7 \times 60}{336.8 \times 360} = 0.0256 \text{ sec.}$$

$$\text{Temperature lag} = \frac{11 \times 60}{336.8 \times 360} = 0.00545 \text{ sec.}$$

$$\text{Combustion lag} = \frac{11.8 \times 60}{336.8 \times 360} = 0.00583 \text{ sec.}$$

The comparatively low values of both the temperature lag and combustion lag of the card of Fig. 8 indicate a quick ignition and rapid combustion.

The expansion m-curve rises sharply from a to b, but somewhat less sharply from b to c. This is the period during which the temperature is dropping, although the combustion continues at a fair rate. At point c the heat generated by the combustion just balances the heat given up to the walls. This heat is comparatively small, therefore it is safe to assume that shortly afterward the combustion ceases.

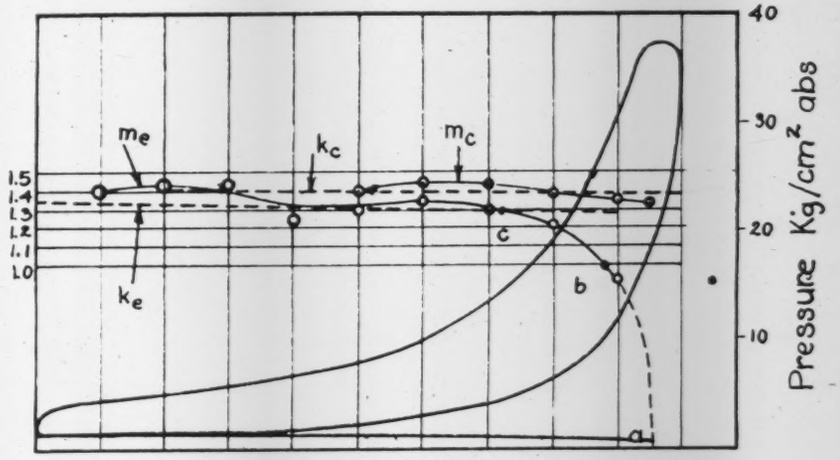

FIG. 9 ANALYSIS OF AN M.A.N. DIESEL ENGINE

From point c the m_c-curve is nearly horizontal for a while, then from 30 per cent stroke it rises moderately, corresponding to the increased influence of the cooling with the increasing exposed wall surface.

The shape of the expansion m-curve is regular, showing a quick ignition, rapid combustion, and effective cooling.

The compression m-curve starts at 90 per cent stroke above the k_c-line. This indicates heat introduction to the gas from the walls. At the beginning of compression the cylinder walls and piston are hotter than the charge and give up heat to the gas. The heat introduction lasts until 83 per cent stroke, where m_c intersects the k_c-line, but from this point on the gas loses heat due to the cooling. The temperature of the compressed charge exceeds that of the walls. The curve runs almost horizontally at the height of 1.34, which is quite normal and indicates fair cooling.

From 10 per cent stroke the m_c-curve rises and at 6.5 per cent it intersects the k_c-line again, indicating heat introduction. This is due to the ignition which took place at 10.7 per cent stroke.

In the following a number of actual indicator cards taken from various types and makes of internal-combustion engines are reproduced, results of analysis given, and certain conclusions drawn. Unless otherwise stated, all of the cards reproduced and analyzed are considered accurate enough to permit such an analysis. However, since the accuracy of the indication depends upon a great

[4] If the compression ratio is not known, an approximate method of ascertaining same is given in *Engineering*, July 18, 1924, p. 101.

many factors, there is always a possibility that a card is inaccurate and hence also the analysis and certain conclusions which have been drawn.

Air-Injection Diesel Engines

M.A.N. Diesel. The diagram reproduced in Fig. 9 was taken from a one-cylinder, vertical, 4-cycle M.A.N. Diesel engine; 12.6-in. bore and 18.9-in. stroke, operating at a speed of 220 r.p.m. The clearance volume was 52.5 cu. in. and the compression ratio 13.1 to 1.

The card was taken on November 19, 1925, in Professor Naegel's laboratory, Technical Institute, Dresden, with a Rosenkrantz indicator. The rig was exceptionally accurate, and the record is considered reliable.

The spring scale was 1.5 mm. = 1 kg. per sq. cm. pressure. The zero-pressure line was drawn 1.5 mm. below the atmospheric

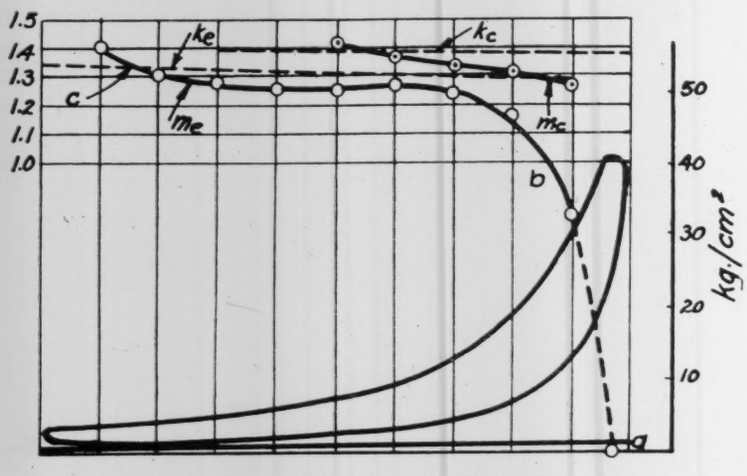

Fig. 10 Three-Cylinder 300-Hp. Diesel Engine

line. The length of the card is 87.9 mm. Corresponding to a compression ratio of 13.1 to 1, the zero-volume line was drawn at a distance of 87.9/12.1 = 7.26 mm. from the right end of the card. The stroke was then divided into ten equal parts and, by using the graphical construction described for each point, the value of m determined, both for the expansion and compression line. The compression line is very flat in the first half of the stroke, which makes the construction uncertain.

In examining the expansion m-curve, we find that the maximum pressure occurs at 5 per cent, the maximum temperature at 12 per cent and the maximum heat content at 28 per cent piston stroke. With a 4.75 connecting-rod ratio the corresponding crank angles are 23.5, 37 and 59 deg. The temperature lag is 37–23.5 = 13.5 deg., and the combustion lag is 60–37 = 23 deg.

Knowing the engine speed, the pressure lag, temperature lag, and combustion lag can be expressed as 0.0178, 0.0122, and 0.0174 sec.

The comparatively low values of both the temperature lag and combustion lag indicate a quick ignition and rapid burning.

The expansion m-curve shows a regular trend. It rises sharply until b, where it has the value 1. From b to c the rise is moderate. This is the period when the injection already has ceased, but the change is still burning. At point c the heat generated by the combustion just balances the cooling loss. Shortly afterward the combustion ceases.

Beyond point c the m-curve is almost horizontal, rising but very slightly. This part of the curve indicates a moderate cylinder cooling.

The compression m-curve is almost horizontal at the height of 1.4. Since the adiabatic k has a value of about the same magnitude at this temperature, the heat exchange between the gas and the wall is insignificant. For the greater part of the stroke there seems to be a heat introduction, coming from the hot piston and cylinder walls. At the end of the stroke the m-curve shows that heat is given up by the gas, because the temperature of the compressed charge evidently exceeds that of the walls. However, the absorption of heat by the walls seems to be very slight. The whole compression m-curve shows that the engine is only moderately cooled.

Both the expansion and compression m-curves show characteristics of a well-adjusted high-grade Diesel engine with good atomization, quick ignition, rapid burning, and moderate but uniform cooling.

Multi-Cylinder Diesels. The indicator diagram reproduced in Fig. 10 was taken from a 16½-in. by 24-in., 3-cylinder, 4-cycle American-made Diesel engine. The engine had a compression ratio of 14.7 to 1 and ran at 205 r.p.m. when the card was taken.

The measured b.hp. was 310 with a fuel consumption of 0.448 lb. per b.hp-hr.

A Maihak indicator was used with a spring scale of 1 kg. per sq. cm. = 1 mm., and the indication is considered accurate.

From the area of the card the indicated mean effective pressure is 103.5 lb. per sq. in., corresponding to 137.5 i.hp. per cylinder. This gives a mechanical efficiency of 310/(3 × 137.5) = 0.751.

The expansion m-curve has a regular appearance. It shows a quick injection and ignition with moderately fast burning. The a-point (maximum pressure) is at 3 per cent stroke = 18 deg. crank angle. The b-point (maximum temperature) is at 35 per cent stroke = 37 deg. crank angle. The c-point (maximum heat content) is at 85 per cent stroke = 130 deg. crank angle.

From this the temperature lag is 19 deg. and the combustion lag 93 deg., corresponding to 0.0155 and 0.077 sec. The latter indicates a rather slow burning.

The compression m-curve is very uniform. It shows a heat introduction in the first half of the compression stroke and heat rejection in the second. The indication is of a good and uniform cooling.

Figs. 11 and 12 show indicator diagrams of another engine of the same make. It is a 6-cylinder, 4-cycle Diesel engine of 13 in. bore by 18 in. stroke, 350 rated b.hp.

The engine was tested under different loads and speed conditions. Diagram a, shown in Fig. 11, was taken at an engine speed of 276 r.p.m.; and diagram b, shown in Fig. 12, at 264 r.p.m. The indicated m.e.p. were 90.2 and 106.4 lb. per sq. in., respectively.

The m-curves for both tests are very similar in appearance. The location of the characteristic points are:

		Per cent stroke		Crank angle, deg.	
		a	b	a	b
a	(maximum pressure)...	2	3	15	18.5
b	(maximum temperature)	20	17.5	48.5	45.5
c	(maximum heat).....	none	88	none	135

From these values, the temperature lags are 33.5 deg. = 0.0202 sec. and 27 deg. = 0.0171 sec. The combustion lags are afterburning and 89.5 deg. = 0.0566 sec.

These results show that the burning was sluggish in this engine, and that it was slightly better when running at heavier load and lower speed than at lighter load and high speed. The fuel consumption, which was 0.35 lb. per i.hp. for full load, bears out this conclusion.

The compression m-curve, on the other hand, is lower in b, in fact low enough to indicate excessive cooling. Both a and b show a noticeable drop in the m-curve near the end of the compression stroke. The probable reason is an overcooled cylinder head. The diagrams also show a late opening of the exhaust valve.

Burmeister & Wain Heavy Marine Engines. Figs. 13 and 14 are reproductions of diagrams taken from Burmeister & Wain heavy marine Diesel engines. The smaller engine, Fig. 13, has 6 cylinders of 500 mm. bore by 900 mm. stroke, and operates at 140 r.p.m. The compression ratio was assumed to be 13.5 to 1. The engine was built in March, 1924, for the ship *Kurina Uaru*. It delivered 816 hp. on block test. The fuel consumption was 0.177 kg. per hp-hr., using Solar oil. The indicator was a Maihak instrument, with a spring scale of 1.025 mm. = 1 kg. per sq. cm.

The expansion m-curve has a favorable appearance, showing a rapid steady rise throughout. The locations of the characteristic points are:

		Per cent stroke	Crank angle, deg.
a	(maximum pressure).....	3.4	20
b	(maximum temperature).....	8.3	30
c	(maximum heat).....	35	67

Hence the temperature lag is 10 deg. crank angle = 0.012 sec. and the combustion lag, 37 deg. crank angle = 0.044 sec. The analysis indicates excellent combustion characteristics. The fuel consumption, which was 0.39 lb. per b.hp. and 0.29 lb. per i.hp., confirms this conclusion.

The compression *m*-curve runs somewhat high, indicating a moderate cooling.

The larger engine (Fig. 14) had 6 cylinders, 630 mm. bore by 1300 mm. stroke. The compression ratio was assumed to be 13.5 to 1. The engine was built in 1921 for the motorship *Leise Maersh*. It delivered on block test 1125 b.hp. at 88 r.p.m. The fuel consumption was given as 0.175 kg. per hp-hour using Solar oil. The same Maihak indicator was used with a spring scale 1.03 mm. = 1 kg. per sq. cm.

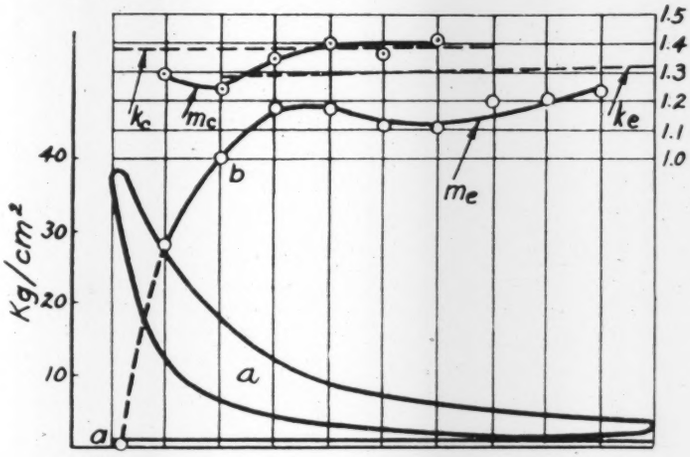

FIG. 11 SIX-CYLINDER 350-HP. DIESEL ENGINE, RUNNING AT 276 R.P.M.

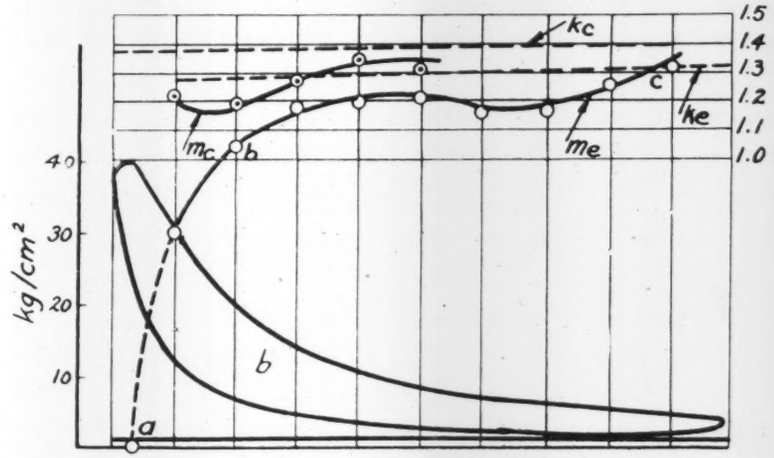

FIG. 12 SAME AS FIG. 11. RUNNING AT 264 R.P.M.

The expansion *m*-curve of this engine is equally favorable. The locations of the characteristic points are:

a.... 3.7 per cent stroke = 20.5 deg. crank angle
b....12.7 per cent stroke = 38.5 deg. crank angle
c....25.0 per cent stroke = 55.5 deg. crank angle

The temperature lag is 18.5 deg. c.a. = 0.0342 sec., and the combustion lag 17 deg. c.a. = 0.032 sec.

The temperature lag is longer and the combustion lag is shorter in the large engine than in the small one, which indicates that the spray action, including injection, pulverization, and ignition, was better in the small engine; combustion, on the other hand, was better in the large engine. In fact a combustion lag as short as 17 deg. crank angle is quite exceptional and is probably due not only to the low speed but also to a well-shaped combustion chamber, good penetration, and sufficient turbulence. The fuel consumption, which was 0.385 lb. per b.hp-hr. and 0.289 lb. per i.hp-hr., bears out this conclusion.

The compression *m*-curve runs fairly high, indicating a moderate cooling. The cooling frequently offers difficulties in large cylinder sizes.

U. S. Navy Submarine Diesel Engine. A 1000-hp., 6-cylinder, air-injection Diesel engine built by the New York Navy Yard in 1922 for the U. S. Submarine S-13 gave the indicator card shown in Fig. 15.

The cylinders were $17^3/_4$ in. by $16^9/_{16}$ in.; compression ratio

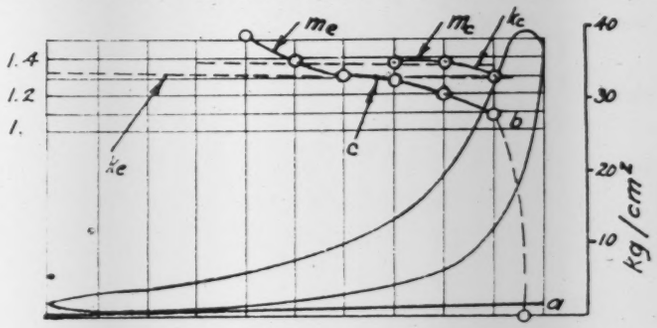

FIG. 13 BURMEISTER & WAIN 800-HP. ENGINE

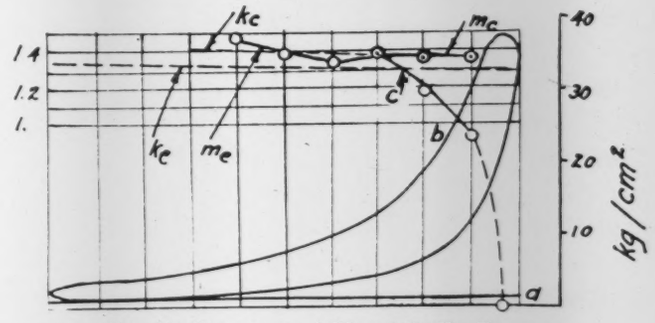

FIG. 14 BURMEISTER & WAIN 1100-HP. ENGINE

13.25 to 1, and the engine speed was 425 r.p.m. The spring scale of the Lehmann and Michels indicator used was 1 in. = 500 lb. per sq. in.

The rise of the expansion *m*-curve is gradual, which is obviously due to the comparatively high engine speed. On the other hand, it keeps on going up for a considerable period, which indicates good combustion conditions.

The maximum pressure occurs at 19 deg. crank angle, the maximum temperature at 51 deg. crank angle and the maximum heat content at 77 deg. crank angle. Hence the temperature lag is 32 deg. = 0.0125 sec. and the combustion lag is 26 deg. = 0.01 sec. In degrees the temperature lag is rather long, but in seconds it corresponds almost exactly to the 500 mm. (19.65 in.) Burmeister & Wain engine which ran at 144 r.p.m.

The combustion lag is very short. The combustion is completed within one-half of the expansion stroke, which is remarkable for a 425-r.p.m. engine. A spray suited to the combustion chamber and good turbulence is perhaps responsible for the favorable combustion; this is also proved by the exceptional consumption figure, 0.279 lb. per i.hp-hr. The fuel consumption per b.hp-hr. was less favorable (0.424 lb.), due to the rather low mechanical efficiency (66 per cent).

The compression *m*-curve is very regular, indicating a very satisfactory cooling, that of the cylinder head being particularly good.

German Submarine Diesel. The indicator diagrams shown in Figs. 16 and 17 were taken at the New York Navy Yard from a 3000-hp. 10-cylinder ex-German submarine Diesel engine, $20^7/_8$ in. bore and $20^7/_8$ in. stroke. The tests were made at various speeds, the engine being run at the maximum power possible without smoking at each speed. The cards were taken with a Lehmann and Michels indicator, with a 500 lb. = 1 in. spring scale. For the cards here reproduced the engine speeds were 175 r.p.m. and 283 r.p.m., respectively.

The expansion *m*-curves of both diagrams are rather low and do not reach the adiabatic line within the distance examined. The probable explanation is that by increasing the load as much as

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possible without causing a smoky exhaust the engine practically always ran under an overload for the respective speed and did not get enough oxygen to burn all of the fuel completely.

The locations of the characteristic points are:

		Per cent stroke		Crank angle, deg.	
		175 r.p.m.	283 r.p.m.	175 r.p.m.	283 r.p.m.
a	(maximum pressure).....	1.6	2.8	13.5	18
b	(maximum temperature)..	16.8	18.2	44.5	46.5
c	(maximum heat).....	none		none	

The temperature lags are 21 deg. and 18.5 deg. crank angle, respectively, corresponding to 0.02 and 0.011 sec.

The fuel consumption was 0.481 lb. per b.hp-hr. at 175 r.p.m. and 0.462 lb. per b.hp-hr. at 283 r.p.m. The mechanical efficiencies were 0.735 and 0.73, respectively. Hence the fuel consumption per i.hp-hr. was 0.353 and 0.337 lb., which is somewhat high and bears out our analysis.

The compression *m*-curve drops almost to the isothermic line at the end of the stroke, which shows that the cooling of the cylinder head was very forceful.

Worthington Air-Injection Diesel. A 22½-in. by 38-in. one-cylinder Diesel engine built at the Snow Holly Works of the Worthington Pump andMachinery Corp. in 1915 gave cards shown in Figs. 18, 19, and 20. The engine was rated at 200 hp. and delivered successively 190, 204 and 225 b.hp. at 150 r.p.m.

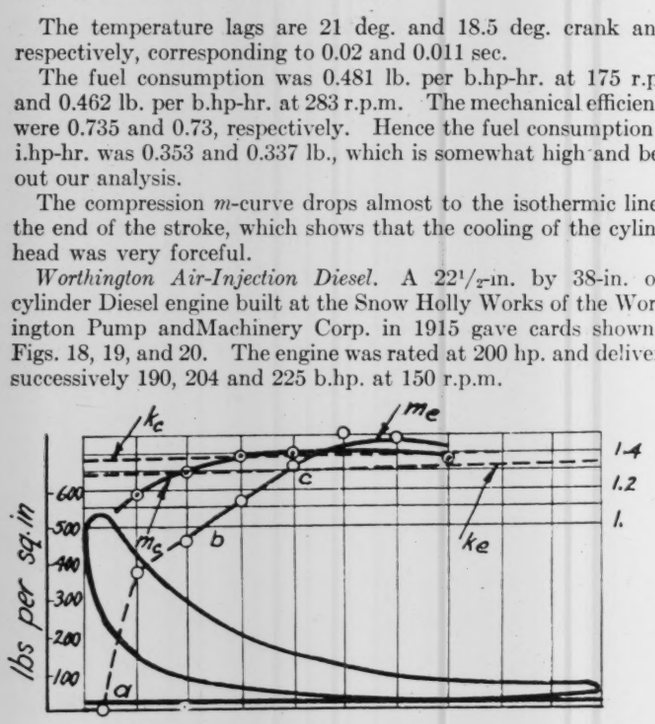


Fig. 15 U. S. Navy Yard Submarine Diesel

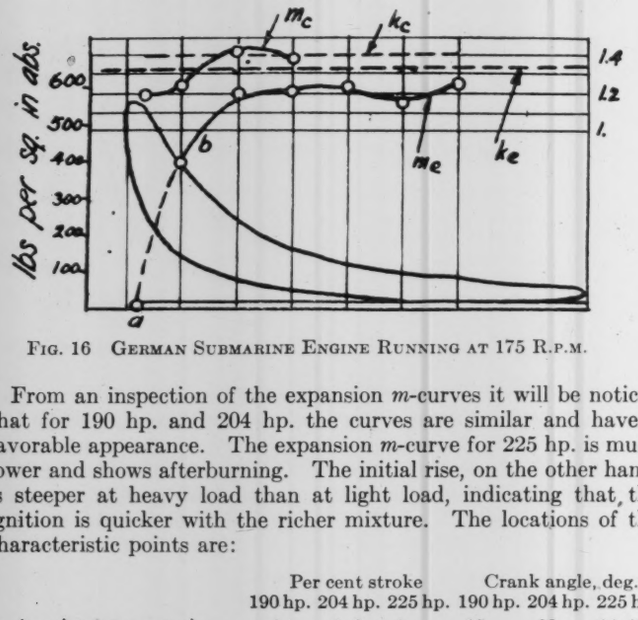


Fig. 16 German Submarine Engine Running at 175 R.P.M.

From an inspection of the expansion *m*-curves it will be noticed that for 190 hp. and 204 hp. the curves are similar and have a favorable appearance. The expansion *m*-curve for 225 hp. is much lower and shows afterburning. The initial rise, on the other hand, is steeper at heavy load than at light load, indicating that the ignition is quicker with the richer mixture. The locations of the characteristic points are:

		Per cent stroke			Crank angle, deg.		
		190 hp.	204 hp.	225 hp.	190 hp.	204 hp.	225 hp.
a	(maximum pressure).....	2	4.6	4	15	23	21.5
b	(maximum temperature)..	8.9	8.5	6.6	31.5	29.5	27.5
c	(maximum heat).....	4.8	47	none	82	81	none

Computing from these the temperature and combustion lag, we get:

	Temperature lag		Combustion lag	
Horsepower	Deg. crank angle	Seconds	Deg. crank angle	Seconds
190	18	0.018	50.5	0.056
204	7.5	0.0083	51.5	0.057
225	6	0.0067	afterburning	

We notice that the temperature lag is very short and decreases with increasing load, corresponding to the quicker ignition of the richer mixture. In spite of this, it takes a longer time to complete the combustion when the air contains more fuel, as can be seen from the increase of the combustion lag.

The compression *m*-curves run very regularly for the greater part, but drop appreciably at the end of the stroke, which indicates a forceful cooling of the cylinder head.

From the above analysis it is evident that the injection and ignition are excellent in this engine, due to a satisfactory spray valve and correct timing. The combustion is good at normal load, but less so at overload. The reason why the engine could not stand overloading better could not be ascertained.

The fuel consumption was given as 0.423 lb. per hp-hr. at full load. With a mechanical efficiency of 0.698 the fuel consumption

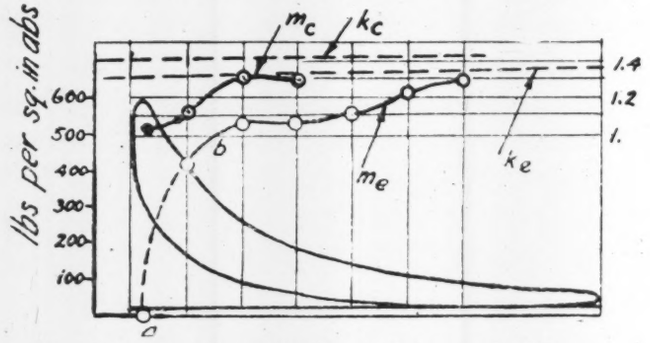


Fig. 17 German Submarine Engine Running at 283 R.P.M.

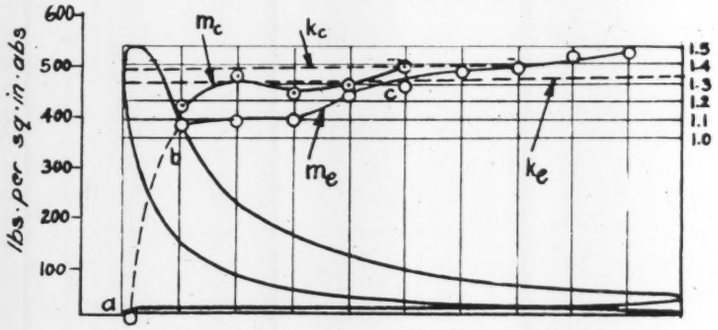


Fig. 18 Underload, Worthington Diesel Engine

per i.hp. was computed as 0.296 lb. per hr. for full load. In view of the above analysis, this value seems reasonable.

Nordberg Two-Cycle Diesel. Figs. 21, 22, and 23 show full-load cards taken from 2-stroke-cycle air-injection Diesel engines built by the Nordberg Manufacturing Co. Fig. 21 refers to a 15-in. by 20-in. cylinder which develops 110 b.hp. at 225 r.p.m. The clearance volume was given as 235 cu. in., with which the compression ratio would be 15 to 1.

The expansion *m*-curve shows a sluggish initial burning; the maximum temperature is not reached until 28 per cent stroke and the combustion is not completed within 70 per cent stroke. The compression *m*-curve is exceptionally low, indicating excessive cooling. However, it is possible that the value of the clearance volume has been given too low and that with the correct value both the m_c- and m_e-curves would be slightly higher.

Fig. 22 refers to a 20¾-in. by 26-in. cylinder, which develops 250 b.hp. at 180 r.p.m. With 605 cu. in. clearance volume the compression ratio is 14.5 to 1.

The expansion *m*-curve shows a more rapid ignition than that of the 110-b.hp. cylinder, reaching the maximum temperature at 21 per cent stroke. The progress of the combustion is also more satisfactory, the maximum heat being at 58 per cent stroke.

The compression *m*-curve runs rather high, indicating that the cooling is not very ample.

Fig. 23 refers to a 28-in. by 44-in. cylinder, which develops 500 b.hp. at 120 r.p.m. With 1840 cu. in. clearance volume, the compression ratio is 14.7 to 1.

The expansion *m*-curve shows a rapid ignition and good combus-

tion. Maximum temperature is at 13 per cent and maximum heat at 50 per cent stroke.

The compression *m*-curve runs fairly low, but rises at the end of the stoke, indicating that the cooling of the cylinder head is not as forceful as that of the cylinder.

The temperature and combustion lags for the respective engines are given in the following table:

	Temperature lag		Combustion lag	
Horsepower	Deg. crank angle	Seconds	Deg. crank angle	Seconds
110 b.h.p.	48	0.0350	afterburning	
250 b.h.p.	35	0.0324	43	0.0398
500 b.h.p.	30	0.0417	45	0.0625

SOLID-INJECTION HIGH-PRESSURE ENGINES

De La Vergne S.I. Engines. The cards shown in Figs. 24 and 25 are typical for solid-injection engines. They have no pronounced constant-pressure lines and show some similarity to the Otto cycle. They frequently are called mixed-cycle diagrams. The cards were taken from a single-cylinder 100-hp. De La Vergne solid-injection engine of 17 in. bore and $27\frac{1}{2}$ in. stroke. The engine speed was 200 r.p.m. Fig. 24 represents full load, and Fig. 25, 75 per cent load. A Lehmann and Michels indicator was used. The fuel consumption is given as 0.41 lb. per b.hp-hr. for full load operation and 0.42 for 75 per cent load.

The expansion *m*-curve on the full load card is very favorable. It shows rapid ignition and fast burning, the combustion being completed at about half-stroke, from which one would conclude that this engine would stand considerable overloading.

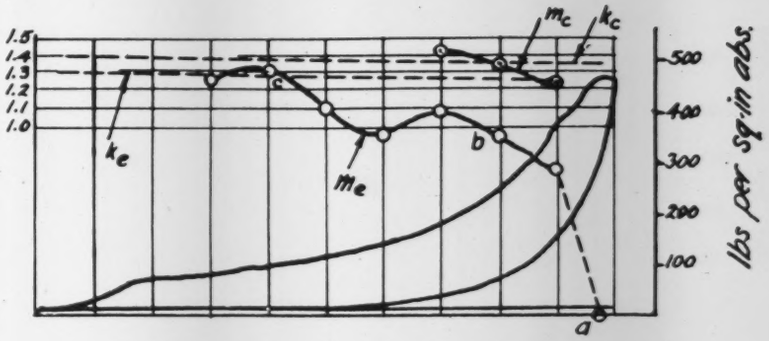


FIG. 22 NORDBERG TWO-CYCLE ENGINE. 250 B.HP. PER CYLINDER

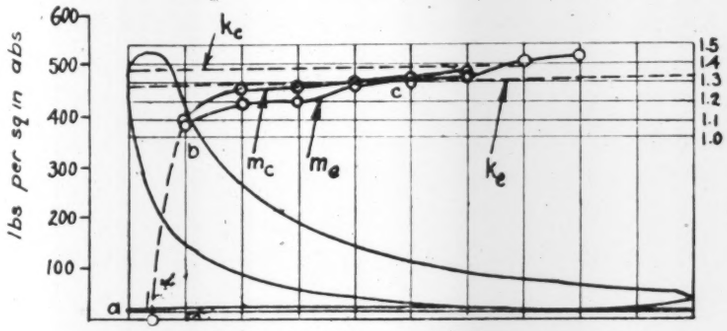


FIG. 19 FULL LOAD, WORTHINGTON DIESEL ENGINE

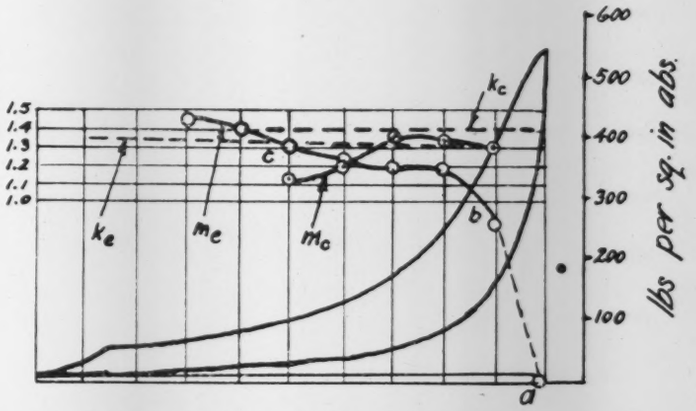


FIG. 23 NORDBERG TWO-CYCLE ENGINE. 500 B.HP. PER CYLINDER

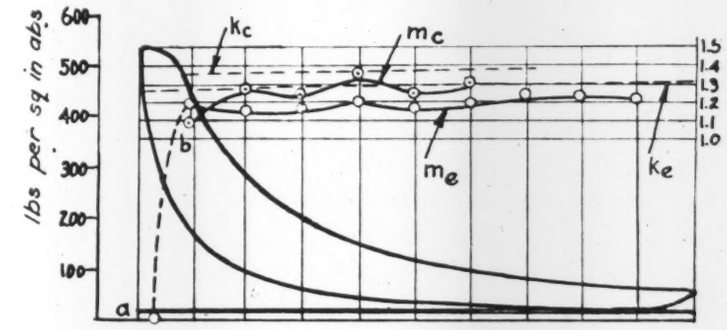


FIG. 20 OVERLOAD, WORTHINGTON DIESEL ENGINE

The expansion *m*-curve corresponding to partial load is not quite as favorable. The temperature lag is approximately the same, about 26 deg. crank angle for either load, which indicates a rapid ignition. The combustion, however, is appreciably slower on light load with an indication of afterburning.

The less perfect combustion on partial load can perhaps be explained in this particular case by an overcooled engine. The compression *m*-curve at full load is very regular, indicating good uniform cooling. At 75 per cent load, on the other hand, the *m*-curve runs rather low throughout. Throttling of the cooling water might have relieved this condition.

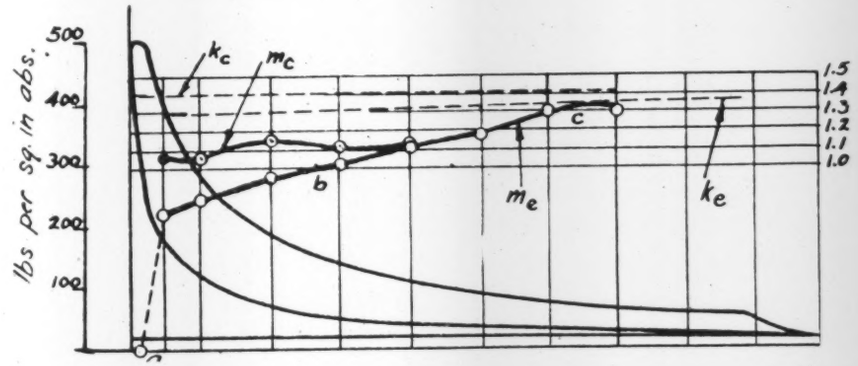


FIG. 21 NORDBERG TWO-CYCLE ENGINE. 110 B.HP. PER CYLINDER

Solid-Injection Engine with Rapid Ignition. Analysis of an indicator diagram for another solid-injection engine is shown in Fig. 26. The card was taken from a single-cylinder 17-in. by 19-in. 4-cycle engine delivering 90 b.hp. at 257 r.p.m. A Maihak indicator was used with a 268-lb. spring. The fuel consumption is given as 0.417 lb. per b.hp-hr.

The expansion *m*-curve shows a steady, gradual rise, indicating a quick ignition and fair combustion. The temperature lag is 19.5 deg. crank angle and the combustion lag, 28 deg. crank angle. The great pressure increase in the head dead center indicates that an early injection is partly responsible for the rapid ignition and burning.

The compression *m*-curve is rather high, indicating insufficient cooling.

Falk Experimental Engine. The Falk Corporation of Milwaukee, Wis., experimented with solid-injection engines of the twin-spray injection type. One of them had four 19-in. by 28-in. cylinders, each of which was fitted with a different type of combustion chamber. The cards shown in Figs. 27, 28, 29, and 30 correspond to cylinders 1–4. A Lehmann and Michels indicator was used. The engine delivered 669 b.hp. at 219.2 r.p.m.

Since no compression ratio was given, this was estimated to be 12 to 1, which corresponds to the indicated compression pressure for solid-injection engines.

The analysis of the expansion line shows afterburning in each of the cylinders, with the possible exception of cylinder No. 1. This afterburning should have manifested itself in a colored exhaust. According to the diagrams, the afterburning was most pronounced in cylinder No. 2.

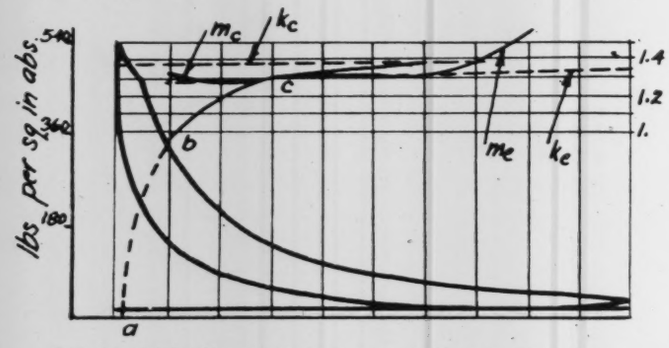


Fig. 24 De La Vergne Solid-Injection Engine, Full Load

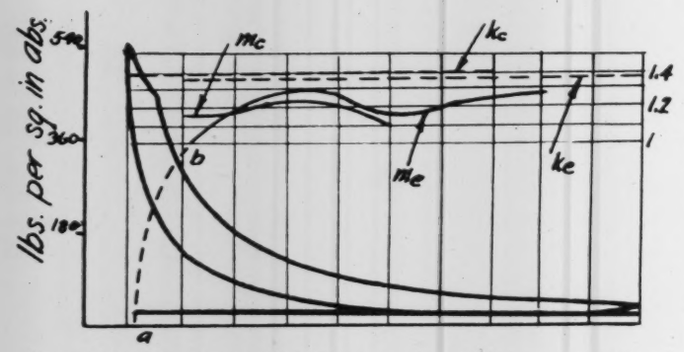


Fig. 25 De La Vergne Solid-Injection Engine, 75 per cent Load

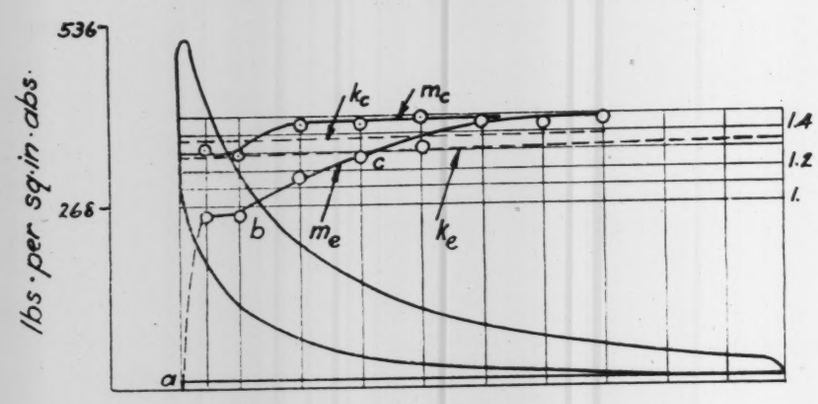


Fig. 26 Solid-Injection Engine with Rapid Ignition

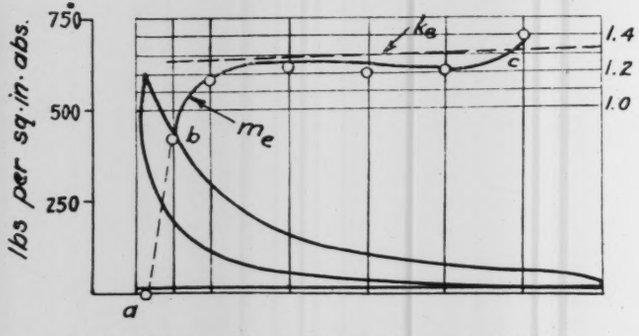


Fig. 27 Cylinder No. 1, Falk Experimental Engine

The third cylinder shows an earlier ignition, reaching its maximum temperature near dead center very shortly after maximum pressure. The temperature lag in each of the remaining cylinders is about 25 deg. crank angle. By an earlier injection this perhaps could have been advantageously reduced. In cylinder No. 4 the drop of the expansion *m*-curve near the end of the stroke may be due to a slight burning of lubricating oil.

Analysis of the compression lines has been omitted.

Low-Compression Oil Engines

Chicago Pneumatic Hot-Bulb Engine. Hot-bulb engines, often called semi-Diesels, have entirely different *m*-curve characteristics, as can be seen in the following example.

The card shown in Fig. 31 was taken from a 30-hp. 12-in. by 12-in. one-cylinder hot-bulb engine, manufactured by the Chicago Pneumatic Tool Company. A Crosby indicator was used in the test. The engine speed was 300 r.p.m.

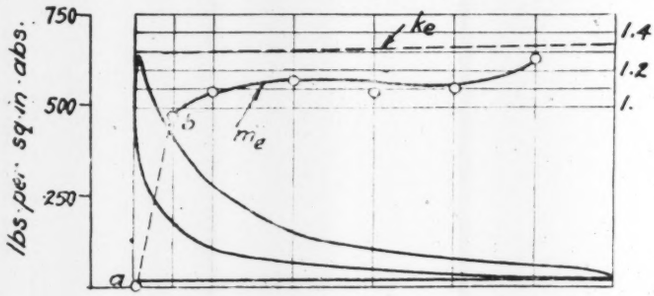


Fig. 28 Cylinder No. 2, Falk Engine

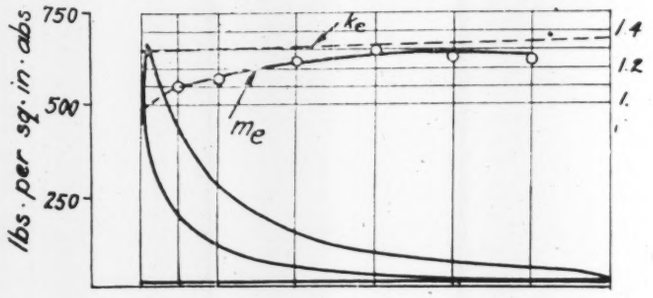


Fig. 29 Cylinder No. 3, Falk Engine

The expansion *m*-curve starts above the isothermal line and is almost horizontal for a good portion of the early part of the expansion stroke. It shows a delayed ignition and also a sluggish combustion. In spite of this, the combustion seems to be completed before the exhaust valve opens. The point *c* of maximum heat content is reached at 65 per cent stroke, corresponding to 102 deg. crank angle. This should give a colorless exhaust in spite of the low thermal efficiency.

The compression *m*-curve is very peculiar, running very high throughout the stroke and dropping below the adiabatic line only near the head dead center. This indicates that the engine is very hot, indeed, and that the charge absorbs heat continually except at the end of the stroke. Water injection is probably responsible for the cooling indicated by the end drop of the compression *m*-curve.

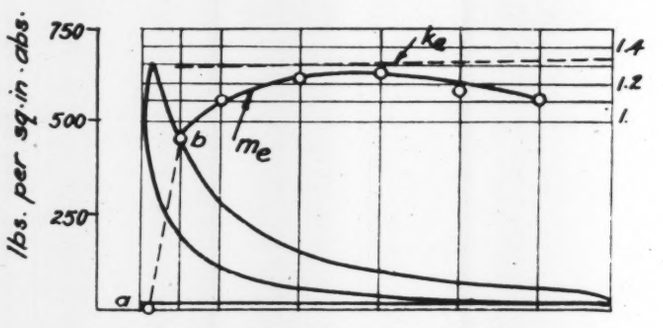


Fig. 30 Cylinder No. 4, Falk Engine

GASOLINE ENGINES

Hispano-Suiza Airplane Engine. Early in 1922 a 300-hp. Hispano-Suiza engine belonging to the Army Air Service was installed in the altitude chamber of the Bureau of Standards and a rather complete series of indicator cards obtained.

The engine tested had a bore of 5.51 in., a stroke of 5.91 in. and a compression ratio of 5.6 to 1. The conditions under which cards were obtained included full-throttle runs at the normal engine speed of 1800 r.p.m. and at air densities corresponding to ground level and to altitudes of 5000, 10,000, 15,000, 20,000 and 25,000 ft. The other major series of cards was obtained at an engine speed of 1200 r.p.m., with the engine so throttled as to develop the power necessary to drive at that speed a propeller capable of absorbing the full power of the engine at 1200 r.p.m.

The indicator used in obtaining the cards was a balanced-type indicator, developed by the Bureau of Standards and described in Report No. 107 of the National Advisory Committee for Aeronautics.

Through the courtesy of the Bureau of Standards, the whole series of 20 cards was available for analysis. One of these is reproduced in Fig. 32.

The card shown in Fig. 32 was taken under conditions corresponding to 5000 ft. altitude. The pressure of the air horn was 25 in. Hg, and its temperature 30.7 deg. fahr. The engine ran under full throttle at 1800 r.p.m.

The expansion *m*-curve has a peculiar shape, which was also found on most of the other cards taken from this engine. In the beginning it rises a little, then it declines until about the middle of the stroke, rising again till the end of the stroke. The variation is between 1.1 and 1.4.

Compared with Diesel engines, we note that while the expansion *m*-curve for Diesel engines starts far below the isothermal line and intersects it 30 to 50 deg. later, with gasoline engines the expansion *m*-curve is above the isothermal from the beginning. Due to the advanced ignition and greater flame propagation, the maximum temperature is reached at the same time as the maximum pressure and a much greater portion of the fuel is burnt at the dead center. In spite of that, complete combustion is seldom found with high-speed gasoline engines. The expansion *m*-curves stay below the adiabatic line, or reach it only near the end of the stroke.

The compression *m*-curves do not permit a rational interpretation. Perhaps evaporation and condensation of liquid gasoline in the mixture are responsible for their erratic behavior.

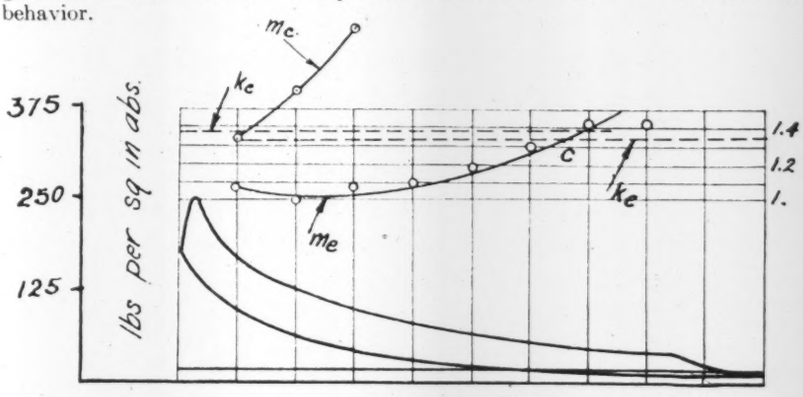


FIG. 31 CHICAGO PNEUMATIC HOT-BULB ENGINE

Bayerische Motoren Werke Motorcycle Engine. The card shown in Fig. 33 was taken from a 2-cylinder, 4-cycle, air-cooled motorcycle engine of 2.68 in. bore and 2.68 in. stroke, manufactured by the Bayerische Motoren Werke, Munich, Germany. The engine had a compression ratio 4.3 to 1. At 1500 r.p.m. it delivered 2.92 b.hp.

A Lehmann and Michels indicator was used in connection with a De Juhász indicating valve.[5]

The expansion *m*-curve is above the isothermal from the beginning, but considerably below the adiabatic, indicating sluggish combustion and afterburning.

The compression *m*-curve is also rather low, indicating an overcooled cylinder.

Napier Lion Airplane Engine. The indicator diagram shown in Fig. 34 was taken in the air from a 450-hp. Napier Lion airplane engine fitted in a D.H. 9 British airplane. A Farnborough indicator was used. This was developed by the Royal Aircraft Establishment[6] and resembles in principle the instrument developed by the Bureau of Standards.

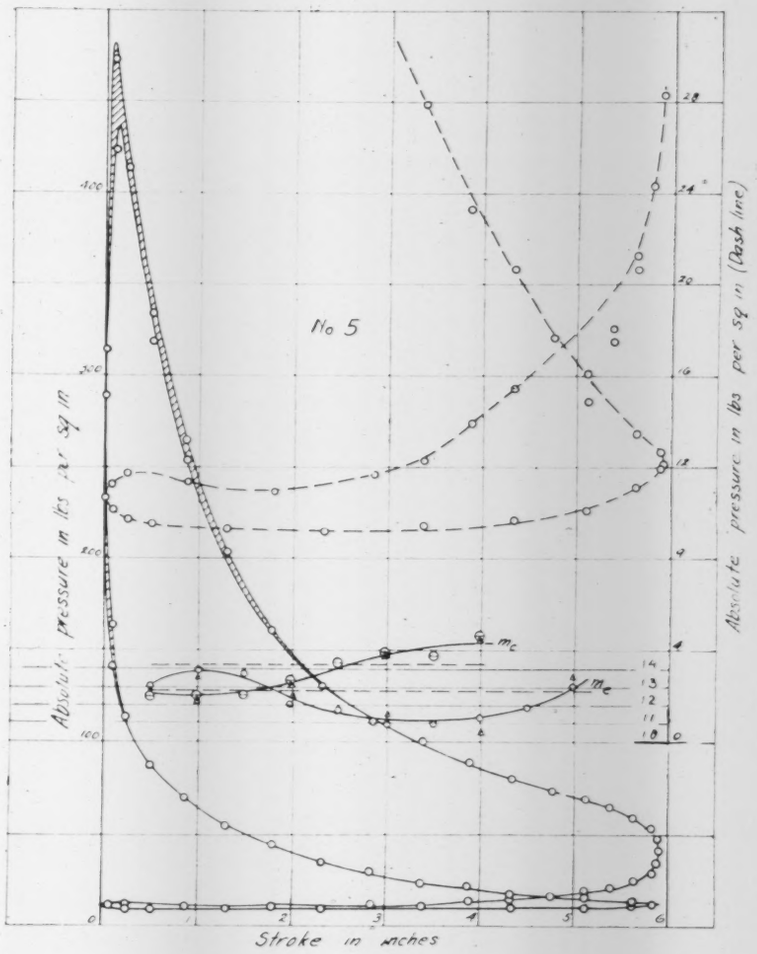


FIG. 32 HISPANO-SUIZA AERO ENGINE. 5000 FT. ALTITUDE, 1800 R.P.M.

The engine had a $5^1/_2$-in. bore, a $5^1/_8$-in. stroke, and a compression ratio of 5.85 to 1. The card reproduced was taken at 10,000 ft. altitude.

The expansion *m*-curve shows a rather late ignition for a gasoline engine. Maximum temperature is not reached until 44 deg. crank angle. This is perhaps partly due to altitude conditions and partly to insufficiently advanced ignition.

The combustion is satisfactory and completed before the end of the expansion stroke.

The compression *m*-curve is fairly high, except near the head, which seems to be cooled sufficiently.

GAS ENGINES

Allis-Chalmers Gas Engine. The gas in a gas engine enters the cylinder completely "vaporized," hence one would expect that the ignition in a gas engine would be much more rapid than in gasoline engines.

[5] For description, see The De Juhász Indicator, by K. J. De Juhász. *Automobile Engineer*, vol. 15, no. 206, Sept., 1925, pp. 292–295.

[6] See description in the Proceedings of the Institution of Mechanical Engineers, 1923, no. 2, p. 137.

An examination of various gas-engine diagrams makes it evident that this is not the case, however. In some engines, particularly those running on lean gases, the maximum temperature is not reached before 40 deg. crank angle. The reason is that these gases have a very low flame velocity. The uniformity of the air-gas mixture and the turbulence in the combustion chamber are other factors that influence the speed of combustion.

Fig. 35 shows an indicator card taken from a 4-cylinder 5500-hp. gas engine, built by the Allis-Chalmers Manufacturing Company and installed at the South Chicago Plant of the Illinois Steel Company.

The cylinder had a 48-in. bore, a 60-in. stroke, and a compression ratio of 6.75 to 1. The engine speed was 83 r.p.m.

The expansion m-curve starts rather gradually. Since the maximum pressure occurs virtually at dead center and maximum temperature only 16 per cent of the stroke later, the temperature lag amounts to 43 deg., corresponding to 0.088 sec., which is an unusually high figure. The combustion is incomplete. The probable explanation of this is that the flame velocity in blast-furnace gas is very low in comparison with gasoline or other gases of higher heating value.

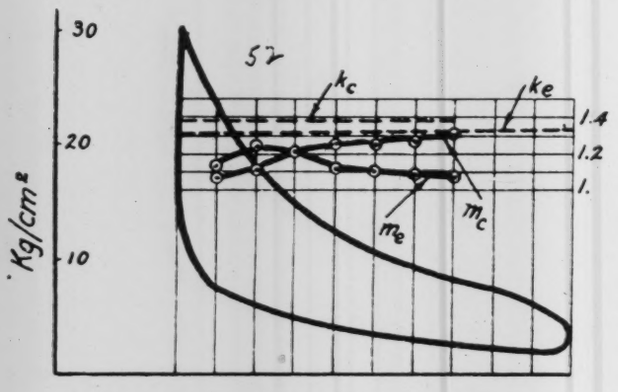


FIG. 33 B. M. W. MOTORCYCLE ENGINE

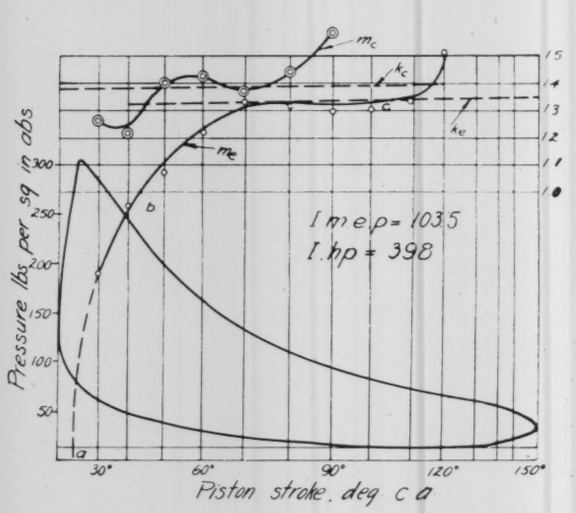


FIG. 34 NAPIER LION AIRPLANE ENGINE

The compression m-curve shows that the cooling of the cylinder head is stronger than that of the liner.

Cockerill Gas Engines. The effect of the quality of the gas on the combustion can be plainly seen in Figs. 36 and 37. The card shown in Fig. 36 was taken from a tandem 2-cylinder, 2000-b.hp. gas engine, of 100 cm. bore by 140 cm. stroke, and 4.49 to 1 compression ratio. The card shown in Fig. 37 refers to a tandem 2-cylinder, 3750-b.hp. gas engine, 130 cm. bore by 150 cm. stroke, and 7.5 to 1 compression ratio. Both engines were built by the John Cockerill Company, Seraing, Belgium. The engine speeds did not differ much, being 100 r.p.m. for the smaller engine and 94 for the larger. The essential difference between the two engines was that the smaller engine was fed with coke-oven gas, which had 4000 calories per cu. m. (450 B.t.u. per cu. ft.), and the larger engine was fed with blast-furnace gas which had only 970 calories per cu. m. (109 B.t.u. per cu. ft.). A Crosby indicator was used in taking the cards and the rig was considered very accurate.

The difference in the expansion m-curves is very pronounced. In Fig. 36, m_e rises sharply, reaching the isothermal line at 6.5 per cent stroke and the adiabatic line at 7.6 per cent stroke, which is very fast indeed.

FIG. 35 ALLIS-CHALMERS GAS ENGINE

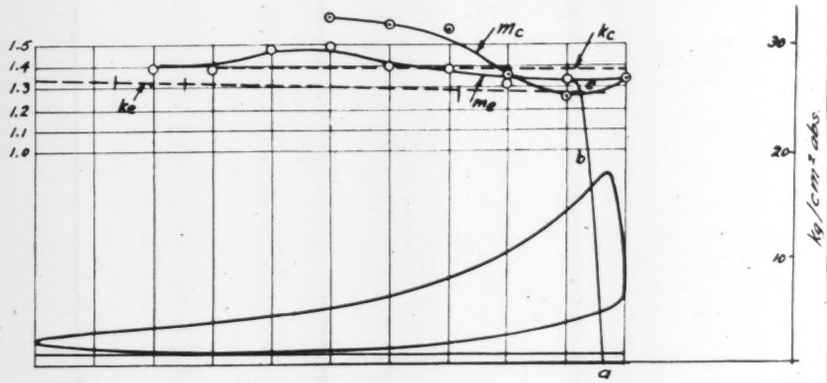


FIG. 36 COCKERILL GAS ENGINE OF 2000 B.HP. RUNNING ON COKE-OVEN GAS

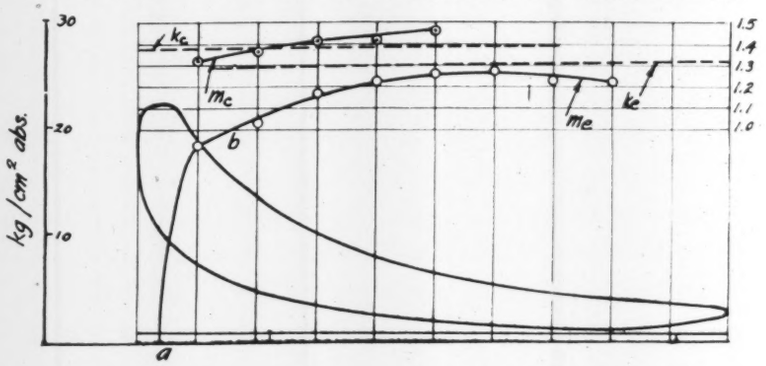


FIG. 37 COCKERILL GAS ENGINE OF 3750 B.HP. RUNNING ON BLAST-FURNACE GAS

In Fig. 37, m_e starts steeply also, apparently due to the considerably advanced ignition spark, but after reaching the isothermal line at 15 per cent stroke it flattens down and does not reach the adiabatic at all. The combustion of the lean gas is so slow that it is not completed when the exhaust valve opens. With the richer gas the combustion is completed within 10 per cent stroke, in spite of the fact that the ignition timing was presumably very close to the head dead center.

The compression m-curves have a regular appearance. That of Fig. 36 drops appreciably near the head dead center, due presumably to an intense cooling of the cylinder head. In Fig. 37 the cylinder-head cooling was partly counteracted by the early ignition, hence the fall of the m_e-curve is less pronounced.

Smoke Abatement, Its Effects and Its Limitations

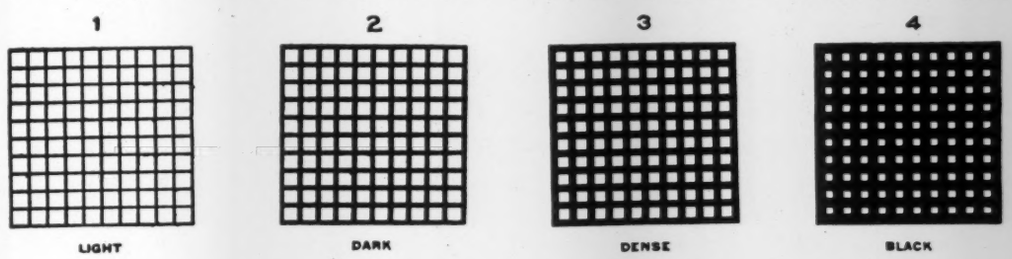
Advantages Accruing to Manufacturers and Public from Smoke Abatement—Anti-Smoke Laws Incomplete in That They Deal only with the Part of the Air-Pollution Evil that is the Less Grave and Less Menacing to Health

By H. B. MELLER,[1] PITTSBURGH, PA.

THE purpose of this paper is to show that smoke abatement as it has been carried on in a number of cities has been of material benefit (*a*) to manufacturers in forcing better combustion methods, making for improved design and longer life of fuel-burning equipment, and lowering fuel cost for a given output; and (*b*) to the public in reducing the volumes of dense smoke emitted from stacks, increasing the percentage of sunshine with its beneficial effects, while decreasing the quantity of soot, thus resulting in lower bills for laundering, artificial light, etc. It will also be brought out that anti-smoke laws have been framed for the purpose of eliminating only a part of the air-pollution evil—*and that part the less grave and less menacing to health;* that the public generally is not aware of the extent and gravity of air pollution; that even the attempts to enforce existing anti-smoke laws are more or less abortive, because of false ideas of economy in providing only a fraction of the force necessary, and that it is high time the spotlight be turned on the air-pollution evil as a public menace second almost to none.

An Anti-Smoke Ordinance and Its Provisions

In describing methods used to minimize dense smoke, Pittsburgh will be used as an example because of the author's experience as enforcement officer in that city during the past six and one-half years. An ordinance had been in operation from December, 1906, until March 3, 1911, when it was declared void on the grounds that, first, the Legislature of Pennsylvania likely had not given the city any sufficient authority to pass ordinances upon the subject of the emission of smoke, and without such authority the city could not act—this, however, was not definitely ruled—and that, secondly, the ordinances were unreasonable. On June 6, 1911, the Legislature passed an act authorizing cities of the second class to regulate the emission of smoke, and in September, 1911, a new ordinance—the present one with one modification, that of the exception of mill heating furnaces and puddling furnaces—was passed. This ordinance (for convenience, the one in force at present, without the exception noted) is as follows:



20% Black 40% Black 60% Black 80% Black

Instructions for Use of Ringlemann Chart

Place the above chart a sufficient distance from the eye to cause the lines to merge similar to appearance of smoke. Compare with the density of the smoke under observation. Ordinance 566 provides penalties for the production or emission of smoke equal to, or of greater density than, scale number three (3) of the Ringlemann Chart. The lines of the chart will merge at from fifteen to twenty feet from the eye.

AN ORDINANCE regulating the production or emission of smoke from any chimney, smokestack or other source within the corporate limits of the city of Pittsburgh, except buildings used exclusively for private residence purposes and flats and apartment houses in which there are less than 6 apartments, and prescribing penalties for the violation of the provisions thereof.

Section 1. Be it ordained and enacted by the City of Pittsburgh, in Council assembled, and it is hereby ordained and enacted by the authority of the same, that in the interpretation of this ordinance, unless the context otherwise requires:

"Persons" shall be considered as referring to all individuals, partnerships, or associations other than corporations.

"Corporations" shall be considered as including all bodies corporate, joint stock companies or associations, domestic and foreign, their lessees, assignees, trustees, receivers, and other successors in interest having any of the powers or privileges of corporations not possessed by individuals, partnerships, or unincorporated associations.

"Chart" shall be considered as referring to the Ringlemann Smoke Chart as published and used by the United States Bureau of Mines.

"Stack" shall be defined as including chimneys, smokestacks, structures and openings of any kind whatsoever, capable of emitting smoke. Smokestacks on locomotive roundhouses shall be deemed parts of locomotives beneath them for the time being.

"Advisory Board" shall be considered as referring to the Board of Engineers appointed by the Mayor to act as advisors on engineering questions to the bureau chief, Bureau of Smoke Regulation of the City.

Section 2. The production or emission within the City, of smoke, the density or shade of which is equal to or greater than Number three (3) of the Ringlemann Chart, from any stack, except that of a locomotive or steamboat, for a period or for periods aggregating two (2) minutes or more in any period of fifteen (15) minutes and the emission of such smoke from any locomotive or steamboat for a period or periods aggregating one (1) minute or more in any period of eight (8) minutes, except for a period not to exceed twenty (20) consecutive minutes, not to exceed once a day, while a new fire is being built therein, is hereby prohibited.

This provision permits the production and emission of any quantity of light smoke and a considerable volume of dense smoke; but, because of the present state of development of fuel-burning equipment, it does not seem feasible to make it more stringent. In some cities the limit is placed at six (6) minutes in an hour, and in some eight (8) minutes in an hour. Many cases of permissible smoke under such ordinances would be violations in Pittsburgh. Besides, an inspector is able to cover more territory in a day if he is not required to time a stack through an hour's period in order to determine whether or not it is violating the ordinance.

A suggestion has been made that all dense smoke, except for six (6) minutes in an hour, and that only when cleaning or building a fire, be prohibited. The author does not believe this practicable, for two reasons: first, the excuse where dense smoke is observed nearly always would be that a fire was being cleaned or a new fire built, and to check up on all such cases would require the full time of a larger force of inspectors than is now employed in any city; secondly, with present equipment and high-volatile coal it is impossible always to prevent the emission of some dense smoke when firing or stoking, though this can be kept within two minutes. The fault has been that the comparatively few persons engaged actively in smoke abatement have been constrained to follow the lead of the manufacturers, tightening up on requirements as improvements were made in design, rather than to set a high standard which the manufacturers would be given a reasonable time to meet. There is now a tendency toward this restriction and manufacturers are showing a commendable willingness to coöperate.

Section 3. The provisions of this ordinance shall not apply to buildings used exclusively for private residence purposes, except flats and apartment houses in which there are more than five apartments.

[1] Bureau Chief, Bureau of Smoke Regulation, City of Pittsburgh. Formerly Dean of the School of Mines, University of Pittsburgh, and Senior Fellow in charge of Air-Pollution Investigation, Mellon Institute of Industrial Research.

Contributed by the Fuels Division for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of The American Society of Mechanical Engineers. All papers are subject to revision.

Be sure to bring this copy with you to the Annual Meeting

There are several reasons for this exemption. At the time the ordinance was passed, natural gas was the usual domestic fuel, and from it little smoke was made. The diminishing supply of this fuel, however, brings the city face to face with a serious problem. Each year large numbers of householders are turning to the use of coal for heating, and few of the furnaces installed for gas are capable of burning bituminous coal without making more dense smoke than would be allowed if it were not for the exemption from the provisions of the ordinance. Comparatively few of the chimneys are of sufficient size to provide the necessary natural draft for bituminous coal. Other reasons for the inclusion of this section were that the attempt to control by law the emission of dense smoke was not looked upon with too much favor at the time, and it was thought unwise to introduce what then seemed an unnecessary regulation; and enforcement would have required a much larger force of inspectors and observers, as there are, within the corporate limits of the city, approximately 100,000 chimneys which are exempt under this section. The section should be repealed.

SECTION 4. No Person or Corporation shall construct, install, reconstruct, alter or repair any furnace, boiler furnace, stack or other apparatus connected with stack, unless he or it shall make application in writing to the Bureau of Smoke Regulation on the form furnished by the said bureau, duly sworn to before a notary public, or any person authorized to administer oaths, for a permit for such construction, installation, reconstruction, alteration, or repair and in and by such application shall give the plans and specifications, showing the style and dimensions of the furnace, boiler furnace, stack or other apparatus connected with a stack intended to be used, a description of the building or part thereof in which such furnace, boiler furnace, or other apparatus is located, including the means provided for regulating the temperature of such building or part thereof and ventilating the same, and generally all provisions made for preventing smoke, together with a statement of the kind of fuel proposed to be used and of the operating requirements to be made of the furnace or furnaces referred to therein and unless such application shall be passed upon by the Bureau of Smoke Regulation, and approved in writing and a permit issued as hereinafter provided; provided, however, that minor or emergency repairs which do not increase the capacity of such furnace, or which do not involve any substantial alteration in such furnace, boiler furnace, stack or other apparatus, and which do not involve any alteration in the method or efficiency of smoke prevention, may be made without a permit.

Any application shall be approved or rejected within ten (10) days after the same is filed in the office of the Bureau of Smoke Regulation.

Upon the approval of any application a copy of which shall be left on file in the office of the Bureau of Smoke Regulation, and upon the payment of the fees hereinafter provided, the Bureau of Smoke Regulation shall issue a permit for the construction, installation, reconstruction, alteration, or repair of such furnace, boiler furnace, stack or other apparatus.

In the event that any such application is rejected by the Bureau Chief, Bureau of Smoke Regulation, the Applicant has the right to appeal from his decision to the Advisory Board. Such appeal shall be made in writing to the Bureau Chief, Bureau of Smoke Regulation, who shall call a special meeting of the Advisory Board within three (3) days for the consideration of the matter. If a majority of the members of the Advisory Board present shall be of the opinion that the application calls for such construction, installation, reconstruction, alteration or repair of furnace, boiler furnace, stack or other apparatus, that there will not under reasonable conditions of operation be produced or emitted from the stack connected therewith, such smoke as is herein prohibited, the decision of the Bureau Chief, Bureau of Smoke Regulation, shall be reversed and the finding of the Advisory Board shall be binding upon the Bureau Chief, Bureau of Smoke Regulation; otherwise the same shall be confirmed. In which latter case the fees to the Advisory Board are to be paid by appellant, who shall first give bond or make other deposit of the funds for the amount of the fees provided for in Ordinance 161, Section 3, approved May 14, 1914.

There might well be a paragraph definitely to the effect that no engineer, contractor, or other person shall do any of the work of construction, installation, reconstruction, alteration, or repair until the required permit has been issued by the Bureau of Smoke Regulation. This rule has been followed in Pittsburgh during the past few years and has obviated much trouble, as previously it happened that sometimes plants would be partially or entirely erected before application was filed, and in cases where changes were necessary additional time and expense were involved.

SECTION 5. For examination of an application for a permit for any such construction, installation, reconstruction, alteration or repair, the Bureau of Smoke Regulation shall collect at the time of issuing such permit, for the use of the City, a fee of two ($2.00) dollars.

The issue and delivery by the Bureau of Smoke Regulation, of any such permit shall not be held to exempt the person or corporation to whom such a permit has been issued or delivered or who is in possession of the same, or whose application has been approved, from prosecution on account of the production or emission of smoke hereby prohibited.

SECTION 6. The Bureau Chief, Bureau of Smoke Regulation, shall keep in the office of the Bureau of Smoke Regulation all applications made, and a complete record thereof as well as of all permits issued. He shall also keep a record of all smoke observations of all stacks and generally of the work done by the Bureau of Smoke Regulation. All such records shall be open for inspection by the public at all reasonable times. He shall in all matters pertaining to the enforcement of the provisions of this ordinance report direct to the Director of the Department of Public Health.

SECTION 7. The Bureau Chief, Bureau of Smoke Regulation, and the smoke inspectors shall have the right to enter in the performance of their duties at all reasonable hours, all premises from which smoke is being emitted, or has been emitted, and any person who shall, after proper identification, deny admittance to such person or persons or interfere with him or them in the performance of his or their duties shall be liable to a fine not exceeding one hundred ($100) dollars or undergo an imprisonment in the Allegheny County Jail or Workhouse of not more than thirty (30) days, or both, at the discretion of the committing magistrate or alderman.

SECTION 8. If any Person or Corporation shall violate any one or more of the prohibitions or requirements of this Ordinance, he or it shall, upon conviction before any police magistrate or alderman of the City of Pittsburgh, be subject to a fine or penalty not exceeding one hundred ($100) dollars for each and every violation thereof, and each day's violation shall constitute a separate offense; or undergo an imprisonment in the Allegheny County Jail or Workhouse of not more than thirty (30) days, or both, at the discretion of the committing magistrate or alderman.

While at times it has been necessary to enter suit in order to force some who otherwise would not comply with the ordinance, such instances have been rare in the past five years. As a matter of fact, for nearly four years it has been possible to secure the necessary coöperation without resorting to suit. And compliance secured through coöperation is very much more valuable to the city than when forced.

SECTION 9. That any Ordinance or part of Ordinance conflicting with the provisions of this Ordinance, be and the same is hereby repealed, so far as the same affects this Ordinance.

"SOOT-FALL" SURVEY

Prior to 1912 little was known about the quantity or quality of solid matter in the air and being deposited throughout the city. Pittsburgh long had been known as the "Smoky City," and a prominent Pittsburgher had the Mellon Institute of Industrial Research conduct a survey to determine the facts. The staff employed included more than fifty scientists, and the results of their work were published in nine bulletins. This was the only comprehensive survey of the kind ever made. Other cities in the United States and the Advisory Committee on Atmospheric Pollution attached to the Meteorological Office, London, England, have collected data on solid matter precipitated from the atmosphere; other agencies have been and are investigating the physiological effects of foreign constituents in the air as breathed.

It should be noted that while the survey was for the purpose of determining *all solid matter*, and the investigation of the effects of *solid matter and noxious and obnoxious gases* in the atmosphere, the anti-smoke ordinance aimed at minimization of *dense smoke only*. Emanations from stacks include—

a Dense smoke—smoke of 60 per cent or greater density, equal to No. 3 or higher on the Ringlemann chart. Less than this is not a violation.

b Light smoke—any visible smoke less in density than No. 3 on the Ringlemann chart; this may be emitted continuously.

c Invisible smoke—not visible to the naked eye when the stack is observed from ground level or at some distance.

All carry solids which do not color the smoke stream, and obnoxious gases.

The Pittsburgh ordinance is similar in principle to those in force in a number of American cities; in fact, it is the basis for many of them. It will be shown that the dense smoke which is prohibited by this ordinance represents only a small percentage of the total solids and fumes responsible for damage to health and property. Of course, it was necessary to start somewhere, and dense smoke, being the most obvious nuisance of this character, offered the opportunity. The error, almost universal, lay in believing that, with visible smoke eliminated, cities would be clean and the menace to public health entirely removed.

A very brief summary of some of the effects of smoke, using the term here in the broader sense, is given below as taken from the bulletins of Mellon Institute.

THE EFFECTS OF SMOKE

Smoke and other items of air pollution fill the atmosphere with acrid, poisonous compounds and soot particles which irritate the sensitive membranes of the eyes, nose, throat, lungs, and gastro-intestinal tract, increase the susceptibility of gastro-intestinal, pulmonary, and naso-pharyngeal disorders, diminish the potential reserve, working capacity, and well-being of the individual, increase fatigue, irritability, and malcontent, and may tend to hasten premature decay.

The smoke content and other impurities in the air have an apparently important bearing on the pneumonia death rate and comparatively little effect on the tuberculosis death rate.

Pneumonia is a catarrhal condition, and a predisposition to it may be prepared by the irritation of the mucous membranes with foreign substances; tuberculosis, being granulomatous in type, in which the microorganisms are sequestered and surrounded by cells, the cure of which is accompanied by fibrosis, may naturally be supposed to be aided in the direction of cure by any deposit which stimulates granulation and fibrosis.

Pneumonia takes its victims from the extremes of life; and also takes off many of our most useful middle-aged business men, i.e., many on whom most has been spent in education, at a time when they are most useful to the community.

Smoke and other solid particles in the atmosphere lessen the duration and intensity of sunshine, reduce the intensity of daylight (the light of short wave lengths, or the blue light, suffering the greater depletion), the limit of visibility, and the diurnal winter temperature; increase humidity, mists, the frequency and duration of fogs, and possibly alter the electrical potential.

Sunshine is an important biodynamic agent. It promotes anabolism, transpiration, and respiration, and increases the percentage of hemoglobin. The blue and ultra-violet rays of sunshine exert a bactericidal effect on pathogenic bacteria, and a tonic, vitalizing influence upon the human organism. Sunshine exerts an exuberant influence on the feelings. Moreover, colorless daylight is superior for visual efficiency, optical health, and effective quality.

Dark clouds have a depressing, devitalizing effect.

Humidity increases the solid, poisonous, bacterial contents of the air, aggravates various pathological conditions of the body, reduces the sensitivity of some sense organs, and depletes the vital potential. Fogs, in addition, increase the inaccuracy of mental work (bank errors), increase the prevalence of diseases, and augment the death rate.

Clear, dry days are anabolic in character and thus produce a superabundance of energy.

Smoke and dust clouds and acid fumes are inimical to the highest aesthetic development of urban communities. They seriously limit not only the possibilities of municipal art, in respect to architecture, statuary, painting, and ornamental gardening, but also limit the possibilities of art education in the community in question. They begrime, deface, decolor, destroy, and corrode interior and exterior artistic effects in color, brick, stone, marble, or metal. Fumes containing carbon monoxide, ethylene, benzene, sulphur dioxide, sulphur trioxide, hydrogen sulphide and carbon bisulphide are injurious to plants. Smoke clouds befoul the persons as well as the dress of the people, limit the range of wearing apparel, and may foster habits of indifference. They obliterate the natural terrestrial panorama of art, the incandescent clouds of the sky. Because of the murky, abject, inartistic appearance of these cities, they are avoided by the wealthy tourist and the retired person of wealth who is in search of a desirable place for residence.

The estimated economic cost of the air pollution nuisance to Pittsburgh (1912–13) was $9,944,740 per annum. No estimate has since been made to determine the economic effect of smoke abatement. St. Louis, Missouri, estimates her loss at present as $15,532,000 per annum, or $18.82 per capita.

The survey showed an average of a little more than a thousand tons of solid matter precipitated from the atmosphere per square mile of area for the year April, 1912, to March, 1913, of which 0.99 per cent was tar, 68.07 per cent ash, and 30.94 per cent fixed carbon; 37.16 per cent of the ash, or 25.29 per cent of the total deposit, was Fe_2O_3. More details are given in comparison with the findings of a second survey made in 1923–1924 and described later.

CORRECTIVE MEASURES TO MINIMIZE DENSE SMOKE

Some of the observations in Mellon Institute Bulletin No. 8, Some Engineering Phases of Pittsburgh's Smoke Problem, are quoted below, with explanations to describe the corrective methods used. It is axiomatic that, in any community, the effort should be so to regulate plants that the natural fuel for that district, which will be the cheapest, may be used without resultant violations of the anti-smoke ordinance. In the Pittsburgh district that fuel is high-volatile or bituminous coal. Fuels foreign to the district may be used in special cases where the owner prefers to pay the higher price rather than to install equipment which will use satisfactorily the cheaper fuel; but sooner or later all want to burn the cheapest fuel on the market, and many seem unable to understand why they should not be permitted to do so regardless of previous agreements with the city or the amount of smoke they might make.

The process of combustion is a simple one [says the Bulletin], being a chemical union of the combustible material of a fuel with the oxygen of the air resulting in the development of heat. In practice, however, many difficulties are encountered which tend to complicate the process, and it is in overcoming these that care is required in the operation and construction of furnaces. The number and nature of the difficulties vary considerably with the fineness of the fuels, the type of furnaces used, the amount and composition of the impurities in the fuel, and variable demands for power.

There are three separate and distinct stages involved in the combustion of coal. First, there is absorption of heat. When fresh fuel is fed to the furnace, its temperature must be raised to the kindling point in order that combustion may begin. Second in order is the distillation and combustion of the volatile portion of the fuel; and third, the combustion of the remaining or carbonaceous portions of the fuel. After the hydrocarbons have been driven off and more or less consumed, the remaining portion of the solid matter is composed mainly of carbon and ash. It is comparatively simple to secure complete combustion at this stage, so that the solution of the smoke problem deals largely with the combustion of the products evolved in the second stage of combustion. Therefore the smokeless combustion of bituminous coal depends upon the construction and operation of furnaces in such a manner that the volatile products evolved in the second stage of combustion are completely consumed before they strike any cooling surfaces which will reduce their temperature below the kindling point. Briefly stated, the principles involved to secure these results are:

a Air in sufficient quantities for complete combustion must be admitted at the proper time.

b The air must be thoroughly mixed with the gaseous portion of the fuel.

c The temperature of the gases must be maintained above their kindling point until the chemical process known as combustion is complete.

It would seem as if this told the whole story and that it would be a comparatively simple matter to have every installation meet the stated requirements. Perhaps it would, if it were not for the human element, from the manufacturer who makes the apparatus in competition for an owner who naturally wants to get the most for his money, to the fireman who feeds the fuel into the furnace. There are, too, such considerations as coöperating with architects to secure the beauty of line at which they aim and at the same time to have a proper chimney for the power or heating plant; and the difficulty, frequently, of securing adequate draft for a new or altered plant from a chimney already in place and designed for a smaller plant.

However, neglecting for the time such specific problems, as well as those of details of correction in specific types of fuel-burning equipment, it may be said that the matter of insuring "smokelessness" as interpreted by ordinance may be considered under the following general heads (interrelated, of course):

1 Draft
2 Combustion space, and
3 Secondary air.

Draft. When natural or chimney draft is depended upon, it is essential that the chimney have a cross-section sufficient to carry away the gases of combustion without undue friction, and a height sufficient to give the maximum draft which will be required. As the draft produced is dependent upon the difference in temperature between the column of hot gases within the chimney and an equal column of air at atmospheric temperature, it follows that the hotter the gases the greater the maximum draft for a given height—and the greater the heat loss, which often, especially in heating plants is lost sight of. As the available draft is the maximum draft less the loss from friction, it follows that the smaller the chimney and the hotter the gases, the greater the difference between maximum draft and draft available. Consequently, unless the volume of gases and their temperature in the stack are known, or until ratings are determined on a standard basis for all types of boilers, it is impossible to do more than make certain assumptions, add a convenient factor of safety, and proportion the chimney. Space will not permit an extended discussion of chimneys; but they have borne so important a part in the minimization of dense smoke that the following statements are deemed necessary.

At first, the catalog recommendations as to stack sizes were used, but this was not found to be a very satisfactory method, and Kent's formula, H.P. $= 3.33 E\sqrt{H}$, where H.P. = horsepower of the boiler, E = effective area of the chimney, in square feet, and H = height of the chimney, in feet, measured from the level of the grates, was adopted as being familiar to every one. For power work and in mill practice it seemed to answer fairly well, and little difficulty has been experienced. It was another matter, however, when it came to low-pressure heating plants, especially the smaller ones, where long firing periods are desirable and indeed are used. It was found that it was not possible to get sufficient data, except by

extensive experimental procedure, which was not provided for in the city budget, on the draft loss through various types of low-pressure heating boilers, and experience proved that two boilers of the same (catalog) rating might show considerable difference in such loss; which meant that in some cases, to secure rating, the allowance in the list of required chimney sizes was insufficient.

In order, therefore, to be able to make proper allowance for the differences in volumes of gases and draft required in different boilers of the same catalog rating, and to know the capacities of boilers in terms of guaranteed steam production, manufacturers were asked to supply, for use in Pittsburgh, the following data:

a Total equivalent evaporation per hour in pounds of clean water, from and at 212 degrees fahrenheit, at the nozzle, 97 per cent dry.

b Grate area in square feet used to obtain this evaporation. If upper and lower grates were used, each was to be stated separately.

c Total coal required, in pounds per hour, to obtain evaporation in (*a*) with grates (*b*), with attention to boiler and fire as may be required.

d Draft, in inches of water, at the outer edge of the smoke collar, necessary to obtain evaporation in (*a*) with grates (*b*) with coal consumption (*c*). The effective area of smoke pipe and chimney to be at least equal to the area of the smoke collar on the boiler.

The tests were to be made in accordance with the code for boiler testing, issued by the American Society of Heating and Ventilating Engineers, except that data were to be furnished for bituminous coal of 13,000 B.t.u. value and 30 to 40 per cent volatile content, and data to be guaranteed by the manufacturer.

Some of the manufacturers were able to supply these data almost at once; others, who had them only for anthracite, found it necessary to have additional tests made with bituminous coal; some did not have any test data and arranged to have tests made for them. While the information for most was furnished promptly and it was thought a table of capacities, fuel consumptions, and chimney sizes could be published by January, 1926, delay in testing, the making of retests that were considered advisable in cases that seemed much out of line, and even changes in design in some cases, have made it inadvisable to publish what would be but a partial list. When the list is available, it will show the prospective purchaser what the manufacturer guarantees to produce, with how much fuel and with what draft. Knowing the fuel consumption, the approximate volume of gases can be computed, as exit temperatures for various types of boilers are fairly well known; and knowing the volume of gases and the draft required, the cross-section and height of stack can be determined with a reasonable certainty that the factor of safety is not greater than it should be, nor, on the other hand, that it will be found inadequate.

Combustion Space. In a large percentage of boilers that were installed prior to, say, 1914 the settings were too low.

For horizontal-return tubular boilers, hand-fired, the following setting heights are now required:

Diameter, inches	Minimum distance between dead plate and boiler shell, inches
48 and less	30
54	32
60	34
66	34
72	36
78	38
84	38

Where it is proposed to use oil or powdered coal as fuel for horizontal-return tubular boilers, the height of the boiler shell above the ashpit must be not less than 60 inches.

In most cases it is desirable to have more than the minimum stated.

In 1922 the Stoker Manufacturers' Association and Boiler Manufacturers' Association adopted the list of minimum and preferred setting heights of boilers given below. As these were found to conform closely with the requirements in effect, they were adopted as standard in Pittsburgh.

A few additional regulations as to settings are as follows:

Each hand-fired water-tube boiler of the highly inclined or vertical type shall have full extension furnace with an arch extending at least four feet back of the grate and firebrick piers installed.

Each chain-grate stoker must have an ignition arch with minimum length equal to two-fifths of the length of grate.

PREFERRED SETTING HEIGHTS OF BOILERS

(Recommended by Stoker Manufacturers' Association and Boiler Manufacturers' Association—1922)

Type of boiler	Multi-retort underfeed		Side-dump stoker		Standard Jones		V-type		Front overfeed		Chain Grate—Nat. draft		Chain Grate—Forced draft	
	Min.	Pfd.	Min.	Pfd.	Min.	Pfd.	Min.	Pfd.	Min.	Pfd.	Min.	Pfd.	Min.	Pfd.
*Hor. water tube	10′ 0″	12′ 0″	10′ 0″	12′ 0″	8′ 0″	11′ 0″	8′ 0″	11′ 0″	8′ 0″	10′ 0″	10′ 0″	12′ 0″	12′ 0″	14′ 0
†Inclined water tube	7′ 0″	8′ 0″	6′ 0″	8′ 0″	6′ 0″	8′ 0″	5′ 0″	7′ 0″	6′ 0″	8′ 0″	6′ 0″	8′ 0″	7′ 0″	8′ 0″
‡Bigelow-Hornsby	5′ 0″	6′ 0″	5′ 0″	6′ 0″	3′ 6″	5′ 0″	3′ 6″	5′ 0″	3′ 6″	5′ 0″	3′ 6″	5′ 0″	6′ 0″	8′ 0″
†Vertical water tube	3′ 0″	4′ 0″	3′ 0″	4′ 0″	3′ 0″	4′ 0″	3′ 0″	4′ 0″	3′ 0″	4′ 0″	3′ 0″	4′ 3″	3′ 0″	4′ 0″
‡Wickes vert. 150-hp	4′ 6″	5′ 0″	4′ 6″	5′ 0″	4′ 6″	5′ 0″	3′ 3″	...	3′ 6″	4′ 6″	4′ 1″	4′ 7″	5′ 0″	5′ 6″
‡Wickes vert. 250-hp	5′ 6″	6′ 0″	5′ 6″	6′ 0″	5′ 6″	6′ 0″	3′ 3″	...	3′ 6″	4′ 6″	4′ 1″	4′ 7″	5′ 0″	5′ 6″
‡Wickes vert. 500-hp	6′ 0″	6′ 6″	6′ 0″	6′ 6″	6′ 0″	6′ 6″	3′ 3″	...	3′ 6″	4′ 6″	4′ 1″	4′ 7″	6′ 0″	6′ 6″
§H. r. t. 72″ diam	8′ 0″	10′ 0″	8′ 0″	10′ 0″	7′ 0″	10′ 0″	7′ 0″	8′ 0″	6′ 0″	8′ 0″	7′ 0″	8′ 0″	8′ 0″	10′ 0″
§H. r. t. 84″ diam	8′ 0″	10′ 0″	8′ 0″	10′ 0″	7′ 0″	10′ 0″	8′ 0″	9′ 0″	6′ 0″	8′ 0″	7′ 0″	8′ 0″	8′ 0″	10′ 0″

Setting heights are measured from—
* Floor to bottom of front header.
† Floor to center line of lower drum.
‡ Floor to center line of tube sheet of lower drum.
§ Floor to bottom of shell.
Horizontally baffled water-tube boilers may be set slightly lower by special permit from the Bureau of Smoke Regulation.

Side-inclined overfeed stokers installed under vertically baffled boilers shall have full extension furnaces. The arch shall extend two feet back of the grate surface.

Where side-inclined overfeed stokers are installed under horizontal-return tubular boilers, full extension settings shall be used.

With low-pressure heating boilers, like the average cast-iron sectional type, combustion is completed somewhere along the line of flow of the gases—the harder the boiler is being pushed, the further along is the point of completion. This is not intended as a criticism, as the author does not wish to criticize anything which has been accepted as passing the legal requirements of an anti-smoke ordinance. The statement is merely one of fact. This type of boiler, if of proper size for the job, provided with an approved device for admitting secondary air, with adequate draft and operated according to instructions, will not violate the ordinance.

Secondary Air. With gas or oil, or coal fed by automatic stokers, the regulation of secondary air is simple. With bituminous coal, hand-fired, it is not. The Bureau of Mines tells us that, with bituminous coal, it is necessary that approximately half the air (the primary) should be fed through the grates and half (the secondary) over the top of the fire. If the fuel is fed uniformly and distillation of volatile matter proceeds in the same way, it is necessary only to determine accurately the volume of secondary air required including the minimum excess for good results, and to supply it. But with hand firing there is an interval, sometimes a long one, between firing periods, and a large quantity of green coal may be fired at a time, with consequent rapid evolution of a large volume of volatile matter. This needs much air to supply the necessary oxygen. Again, when the fire is stoked, additional volatiles are released. In both cases, if there is insufficient secondary air, dense smoke results, more after stoking than after firing; if there is too much air, there is chilling in the firebox as well as unnecessary waste of heat up the chimney. The admission of what may be termed the regular supply of secondary air may readily be arranged for by slides in the firedoors, or by ports; the additional volume needed for approximately three to five minutes after firing or stoking requires in most cases a special device, except that for the low-pressure heating boiler it usually can be effected by "cracking" the firedoor for the necessary time.

Hand-fired furnaces for stationary boilers carrying 50 lb. or more steam pressure and burning bituminous coal are required to be equipped with steam-air siphons, one for each 250 sq. ft. of heating surface. Where less than 50 lb. but more than 15 lb. steam pressure is carried, some other (approved) method of admitting secondary air must be used. For low-pressure boilers, free air openings of not less than 3 sq. in. per sq. ft. of grate surface are prescribed. The alternative in any of these cases is a low-volatile fuel.

Steam jets are said by some to be expensive in operation, because of the amount of steam used; another objection is the noise. It has been the experience here, however, that, if the parts are properly

proportioned and the installation is correct—that is, if the steam supply pipe is of sufficient size, the nozzle has the right opening and the angle over the fire is what it should be, and the sleeve outside the nozzle, siphoning the air, is right—and if the jets are used when, and only when, necessary to maintain a clean stack, the cost of the steam used will be more than offset by the saving in fuel. As a matter of fact, there are many cases on record where the saving has been more than 20 per cent of the fuel bill. A part of the requirement is that the operating valves shall be of the quick-opening type, operated by a lever which is partly across the door, so that at any time the door is opened the jets are turned on, and may be closed by hand or through the operation of a dashpot or similar device, which gives the maximum secondary air at the beginning of the period, gradually diminishing it until the jets are closed completely.

Return-tubular-boiler settings, in addition to steam-air siphons and auxiliary air openings, must have gas-mixing arches, piers, or other acceptable devices.

Low-pressure heating boilers, of the so-called "smokeless" type, usually are provided with ports at or near the rear of the grate for the admission of secondary air. If not too much coal is fired at a time, and the firedoor "cracked" a little for a few minutes, the formation of dense smoke will be prevented. Of course, the firedoor should not be open so wide as to cause too much chilling.

Again quoting from Mellon Institute Bulletin No. 8:

> That there is a reason for such a report as the present one is evidenced by the fact that when smoke observations were made on the stacks of the 152 stationary plants described in this report, about forty per cent of them were violating one of the most lenient smoke ordinances of any large city of the United States. Fifty per cent of the stacks of the hand-fired plants and sixty per cent of the stacks of the front-feed stoker plants were violating the ordinance. The percentages of violations from the other types of stationary plants were small.

Correction has proceeded along two lines: first, all new equipment has been such as could reasonably be expected to be operated within the law; secondly, when equipment was already installed and had been found to violate the ordinance, changes were made. The difficulties found were chiefly as follows:

a Lack of draft. This meant increasing the height of the chimney or building a new one, as the case required.

b Combustion space insufficient. Raising the setting usually corrected this.

c Insufficient secondary air supply and improper regulation. The use of steam-air siphons, ports, etc., has been mentioned.

d Lack of provision for proper mixing of air and gases—straight-draft boiler. Horizontal-return tubular boilers could be corrected by the installation of mixing piers or other arrangement for the purpose. Low-pressure heating boilers of the straight-draft type were required to use a low-volatile fuel; this applies also to this type of boilers under (*c*).

e Improper firing methods. In general, it was found that the coking method best answered the purpose here, proper attention being given to depth of fire, and firebox not to be overloaded with green fuel.

With some types of stokers, trouble was experienced at times with "avalanching."

The gradual elimination of the old causes of excessive smoke, and the regulation of new installations, very materially decreased the volume of tarry matter, as shown by the results of the second survey, described later.

Again quoting:

> The two main sources of smoke in the city and district are the manufacturing plants, which include special furnaces, and the railroads.

Manufacturing Plants. It is true that, because of the cheapness of fuel at the time, little attention was paid to the efficiency of the boiler plants and little effort was made to prevent smoke in heating or metallurgical furnaces. It is by no means true now: plant owners and operating officials coöperate to the fullest extent; millions of dollars have been spent in making changes which improved combustion, and most of the larger plants have combustion engineers and smoke inspectors working in complete harmony with the city officials. The result has been the elimination of dense smoke to the extent that comparatively few violations are now noted. The steps taken to effect this remarkable improvement and the changes made on various types of furnaces in the interest of smoke abatement—which, of course, meant increased efficiency—would take too much space to detail. Suffice it to say that the effort is continuous, and each furnace which is observed to violate the ordinance is treated as a separate problem, to be solved by the plant and city officials in coöperation.

Railroads. Here, too, there has been a remarkable change for the better, as regards smoke. Five railroads operate within the city: namely, the Pennsylvania, the Baltimore and Ohio, the Pittsburgh and Lake Erie, the Pittsburgh and West Virginia, and the Monongahela Connecting. Of these, the first two are most important from the standpoint of fuel burned, the Pittsburgh and Lake Erie enginehouse and storage yard being located outside of the city, and the Pittsburgh and West Virginia and the Monongahela Connecting operating comparatively few locomotives in Pittsburgh.

The limit of dense smoke permitted is closer than with stationary plants, one minute in any period of eight minutes being a violation. The railroad companies from the first have coöperated with the city officials in abating smoke, and each company maintains a corps of inspectors whose sole duty is to observe locomotive operation and to correct conditions responsible for smoke; the total number of such inspectors in the city of Pittsburgh, employed and paid by the railroad companies, is twenty. Contrast with this the force of four smoke inspectors employed by the city to cover all plants within the corporate limits.

Aside from the constant observation by inspectors, the following preventive measures, supplemented by the whole-hearted coöperation of all the railroad officials, have been responsible for the remarkable decrease in the volume of smoke from locomotives.

Nearly all locomotives are equipped with arches. In addition, combustion tubes were used some years ago but have been removed, because, with the methods used here, better results are attained without them.

Locomotives in shifting, work-train and interchange freight service use low-volatile coal. Each locomotive (except those equipped with stokers) in passenger and freight service, working out of a Pittsburgh enginehouse, is supplied with 1000 lb. of low-volatile coal on the front of the tank to keep the fire in proper condition while lying at the enginehouse, to build the fire for the road, and to aid in preventing smoke while the engine is in what is termed the "smoke district."

In the building of new fires at the enginehouses, two methods of lighting are used and two methods for furnishing draft.

By the first method, the fire is built "upside down," so that the volatile matter from the green coal passes through a zone of fire where it may be oxidized and not go into the atmosphere as smoke. The grates are covered with six to eight inches of *high*-volatile coal, on top of which is placed four to six inches of *low*-volatile coal; a bag of wood shavings saturated with oil is spread over the coal and the house blower attached. The fire is then lighted, with the blower turned on just sufficiently to keep down the smoke and to carry the fire over the entire area of the firebox. Air is admitted also through the firedoor while the saturated shavings are burning. As the coal ignites, the firedoor is closed and the blower fully opened. Any further coal supplied while the locomotive is in the storage yard or working in the city is low-volatile.

The second method of lighting fires is with the use of an oil burner, the oil being properly mixed with air before reaching the bed of solid fuel. The preparation is the same as in the first method; it is possible, however, with the use of the oil burner to raise steam in considerably less time. Sufficient air to insure complete combustion is admitted, and the air pressure on the burner is sufficiently high to drive the flame through the coal. The house blower is used fully open and the fire lighted from front to rear of the firebox.

To furnish necessary draft there are steam blower lines and fans. All enginehouses are equipped with steam blower lines, and, in addition, two enginehouses have electrically driven fans. In these two, the steam blower lines are used only in emergencies, which rarely occur; as a matter of fact, it is planned soon to remove the steam lines entirely. The jacks are equipped with hoods which fit closely over the stacks of the locomotives, and with dampers.

The methods of cleaning fires are such that dense smoke is unnecessary and is not permitted. When necessary to bank fires, low-volatile coal only is used.

Be sure to bring this copy with you to the Annual Meeting

A very important factor is the education and coöperation of the engine and house crews.

The saving has been such that there is no question about the continued coöperation of the railroad officials.

Of course, visible smoke only is regulated. The matter of cinders will be mentioned later.

Quoting further from the same publication:

> There are many minor sources of smoke in the city which help to swell the total amount of smoke, such as municipal and contractors' engines, tar and asphalt heaters, etc. These make smoke in the streets and discharge it at low levels, near doors and windows. Smoke from these sources is most annoying and is the cause of many complaints, for it probably causes more relative damage than other smoke emitted at higher altitudes.

Such portable boilers are required to be fired with low volatile fuel, except for a few which have been equipped with steam-air siphons.

In endeavoring to show how the smoke-abatement machine operates, it is possible, in the space allotted, to hit only a few "high spots." No attempt has been made to go into detail which is familiar to all mechanical engineers; nor has the matter of design of boilers and furnaces been touched upon in a critical manner, as it is not within the province of a smoke-abatement enforcement officer. Needless to say, many changes in design have been made to meet anti-smoke ordinances, and many more will be made. Perhaps the greatest needs just now are for a uniform method of rating boilers in terms of output, fuel consumption, and draft requirements, so that chimneys may be properly proportioned; for the elimination of the exemption of any class of buildings or plants from regulation under the ordinance, and for the development of a "smokeless" fuel at a reasonable price for domestic use. With respect to this last, it is to be hoped that the processes known as "low-temperature carbonization" may in the near future be developed to the extent that a semi-coke or char may be obtainable at the same price as bituminous coal, and the cost of the carbonization be paid out of the by-products such as gas, benzene, light oils, etc.

It might be well here to state, not only as a need, but as an absolute necessity, that the city bureau charged with the enforcement of an anti-smoke ordinance shall be entirely free from the harmful influence of politics. Thus only can any measure of success be attained; an enforcement officer who is not himself sincere and impartial in his work, or who has to "take orders" from some one "higher up," is foredoomed to failure. Happily, in Pittsburgh no attempt has been made to inject politics into the bureau. This is well known, and to it is attributable much of the success with which the work of smoke abatement has met.

SECOND "SOOT-FALL" SURVEY

The records of the Bureau of Smoke Regulation of the City of Pittsburgh in 1923 indicated that, as compared with 1913, approximately 80 per cent of the dense smoke (No. 3 or denser, Ringlemann chart) prohibited by ordinance had been eliminated. With the idea of ascertaining whether this was actually true, and also what had resulted in the way of increased or decreased total solid matter being deposited, the author conducted a survey, through Mellon Institute, August 1, 1923, to June 30, 1924, a period of eleven months. The resultant data, which are believed to be as accurate as possible under the conditions, show a marked decrease in dense smoke, with a material increase in solid matter deposited. So that, while Pittsburgh for some time has not merited the title of "Smoky City," it still is a very dirty city. And what is true of Pittsburgh is true of other industrial centers. The evil can and should be corrected.

This second survey was intended to be conducted in exactly the same manner as the survey made in 1912–1913, so that the results might be comparable directly. Samples were collected and analyzed for tar, fixed carbon, ash, and Fe_2O_3. After several months it was thought desirable to collect data which might be compared with those published by the Advisory Committee on Atmospheric Pollution, London, England; consequently samples collected from January to June, 1924, inclusive, were analyzed for tar, combustible other than tar, ash, and Fe_2O_3 in the material insoluble in water, and for combustible, ash, sulphates, chlorine, and ammonia in the material soluble in water.

Samples were collected in jars or cans (glass jars during August and September, 1923, and copper cans thereafter) approximately four inches diameter by ten inches high. These vessels were placed on twelve stations, located in different sections of the city, being the same stations or within a very short distance of those occupied in 1912–1913, and changed monthly.

No.	Station	Location	District
1	Prospect School	Prospect Ave.	Mt. Washington
2	Engine House No. 45	Preble Ave.	Woods Run
3	Allegheny High School	Sherman Ave.	North Side
4	Oliver Building[1]	6th Ave. & Smithfield St.	Downtown
5	Irene Kaufmann Settlement	1835 Center Ave.	Hill
6	Mellon Institute, U. of P.	O'Hara Street	Oakland
7	Hazelwood School	2nd Ave. & Tecumseh St.	Hazelwood
8	Ormsby Park	South 22nd St.	South Side
9	Colfax School	Beechwood Blvd.	Squirrel Hill
10	Brushton School	Brushton Ave.	Brushton
11	Washington No. 2 School	40th and Butler Sts.	Lawrenceville
12	Margaretta School	Margaretta St.	East Liberty

[1] The location of the U. S. Weather Bureau.

The containers were cleaned carefully each time before being placed and a small volume of distilled water poured into each, in order to avoid loss of precipitate through the action of wind. It was necessary also to brace the containers to prevent their being blown over; this was done by surrounding them with bricks.

The samples as collected were weighed and analyzed by the following method (as used in 1912–1913):

Each sample as brought to the laboratory was transferred to a beaker, the container washed with distilled water, the sample filtered through a quantitative filter paper of known weight, the residue with the filter paper dried at 105 deg. cent. for four hours and weighed, and the weight of the paper deducted.

The twelve samples for each month were thoroughly mixed and a representative average sample for the month used for analysis. One gram was wrapped securely in quantitative filter paper and extracted with dry ethyl ether (distilled over sodium) in a Soxhlet extractor to determine the tar. The solution obtained was evaporated, dried at 105 deg. cent., and weighed. The extracted soot was ashed, cooled, and weighed. The iron oxide was dissolved in acid and titrated with potassium permanganate.

The following data were obtained for each month:

Weight of each month's sample for each station, with the area of the container (this area being obtained by measuring the inside diameter with a caliper and calculating the area at the top of the container).

Percentage of tar, combustible other than tar, ash, and Fe_2O_3 for the month.

For the period January to June, 1924, the following additions were made:

The sample from each station was filtered through a quantitative filter paper of known weight into a graduated flask, so that the material soluble in water might be determined by the following method:

Sulphate. One liter or a suitable quantity of the liquid was acidified with hydrochloric acid, boiled, barium chloride added, filtered and barium sulphate weighed. Reported as SO_3.

Chloride. 500 cc. or a suitable quantity of the liquid was titrated with N/10 silver nitrate solution.

Ammonia. One liter of the liquid was just acidified with dilute sulfuric acid and concentrated to 100 cc. This residue was made decidedly alkaline, distilled with N/10 acid, and the ammonia calculated. (Alternative: If the liquid was not appreciably colored, 10 cc. to 25 cc. was directly "Nesslerized" with 1 cc. of Nessler reagent.)

As the samples from any station were so small, and as only one chemist on part time was available to make the analyses, it was impracticable to make a complete determination for each station each month. Therefore a sample for the twelve stations was made for the month by taking a proportionate amount from each. And portions of the individual station samples for the five months January to May were combined for analysis of the insoluble matter for that station.

In considering the results tabulated and comparisons made, it should be borne in mind that the figures are not absolute measures. In the first place, the survey was not intended to be exhaustive; therefore the simplest methods were used which would give an approximate idea of existing conditions. While every care was

used in collecting and analyzing the samples, it cannot truthfully be assumed that the amount of material collected in a container four inches in diameter by ten inches high, placed on the roof of a building where undoubtedly it is more or less influenced by nearby stacks and other conditions purely local, is truly representative of a district covering several square miles. In fact, results from check cans prove this. However, it is believed the primary purpose of the survey has been served, and that the figures given for the city may be taken as approximations of the conditions as they existed during the period.

It will be noted that, except for stations 5 and 6, the total deposits of 1923–1924 exceeded those of 1912–1913. However, the tar content decreased from 9.22 tons per square mile for the period August to June, 1912–1913, to 2.87 tons per square mile for the period August to June, 1923–1924, a decrease of practically 70 per cent by weight, this by reason of the elimination of dense smoke. The increases were in combustible other than tar and in ash, with a slight increase in Fe_2O_3. A part of the increase is due to an increase in the number of stacks operating in the city; a part to the fact that many plants using gas ten years ago now use bituminous coal (this is true especially of private dwellings, apartment houses, and small commercial establishments); some is because, in eliminating dense smoke, in many cases drafts were increased to provide additional air, and as a consequence larger volumes of gases at higher velocities were emitted, carrying more and larger particles than formerly. Much of the increase is due to the present construction of locomotive front ends. Formerly, a large percentage of the solid material drawn through the flues by the high draft necessary was caught in the front end and removed at the end of a trip. Locomotives now have "self-cleaning front ends," so that practically all solid material drawn through the flues goes out the stack.

It is reasonable to suppose that, without the regulation of dense smoke during the past decade, the amount of tar would have increased and conditions in Pittsburgh have been very much worse in 1924 than in 1912–1913.

In 1916 deposits were collected in Pittsburgh and St. Louis, Missouri, over a period of six months, and in Cincinnati, Ohio, over a period of five months. The results, compared with those obtained in Pittsburgh in 1912 (and calculated as for Table 3) and in 1923–1924 are shown in Table 4.

A material increase is shown for Pittsburgh in 1916 over Pittsburgh in 1912–1913, with a decrease for Pittsburgh in 1923–1924 as compared with 1916. Table 4 shows also that the average de-

TABLE 1 DEPOSIT IN GRAMS PER MONTH, AUGUST 1923 JUNE 1924

Month	Stations												
1923	1	2	3	4	5	6	7	8	9	10	11	12	Total
August	0.1070	0.6040	0.1850	0.4100	0.3788	0.0722	0.3200	0.4315	0.1755	0.4265	0.2100	0.1035	3.4240
September	0.1340	0.5620	0.1680	0.4275	0.3310	0.1040	0.2900	0.3960	0.1365	0.2720	0.1840	0.1025	3.1075
October	0.1466	0.7305	0.2582	0.5985	0.2390	0.1578	0.1894	0.2150	0.4360	0.5224[1]	0.2720	0.5055	4.2709
November	0.1542	0.5805	0.2605	0.5423	0.2545	0.2205	0.6666	0.4041	0.2430	0.4541	0.2479	0.1946	4.2228
December	0.3271	0.7172	0.3003	0.4760	0.3043	0.2253	0.6428	0.1709	0.2586	0.6628	0.2427	0.2332	4.5612
1924													
January	0.1915	0.6060	0.3690	0.4688	0.3367	0.2348	0.7050	0.3120	0.3024[1]	0.6705	0.2660	0.3710	4.8337
February	0.1790	0.7413	0.2683	0.6159	0.2370	0.1646	0.3456	0.3252	0.2062	0.2535	0.4836	0.2410	4.0613
March	0.2373	0.5703	0.3885	0.7853	0.3773	0.2501	0.3939	0.5242	0.2885	0.6640[1]	0.6018	0.2345	5.3157
April	0.1033	0.6842	0.2886	0.3448	0.2598	0.2214	0.3715	0.3651	0.2450	0.3725	0.3985	0.1588	3.8135
May	0.1082	0.6227	0.1848	0.3079	0.1997	0.1492	0.2098	0.2358	0.2291	0.8973	0.3428	0.1617	3.6490
June	0.0913	0.4017	0.1263	0.1339	0.0960	0.1514	0.1690	0.1775[1]	0.1840	0.2959	0.3237	0.0915	2.2422
Total	1.7795	6.8204	2.7975	5.1109	3.0141	1.9513	4.3036	3.5574	2.7048	5.4915	3.5730	2.3978	43.5018

[1] In several instances workmen tampered with the containers; the weights in such cases were calculated.

TABLE 2 INSOLUBLE DEPOSIT IN TONS PER SQUARE MILE PER MONTH

Month	Stations												
1923	1	2	3	4	5	6	7	8	9	10	11	12	Average
August	35.7	204.8	56.1	135.8	126.8	28.7	110.2	143.9	57.5	140.8	70.2	34.8	95.4
September	44.2	219.5	66.6	144.4	111.4	35.7	98.3	134.3	53.8	89.7	58.7	33.8	90.9
October	51.8	269.7	91.1	214.5	84.9	57.7	68.8	78.1	158.4	188.7	98.9	181.4	128.7
November	56.7	213.0	95.7	197.7	93.0	77.7	236.1	148.5	89.4	165.3	91.2	60.8	127.1
December	115.3	264.7	106.0	170.5	108.5	82.5	233.7	62.0	94.2	248.3	88.0	83.4	138.1
1924													
January	70.4	220.7	125.5	170.5	123.1	82.8	249.9	114.7	110.0	244.6	97.7	125.2	144.6
February	64.2	273.8	94.5	220.7	84.1	60.3	125.6	118.0	74.8	95.1	175.7	86.4	122.8
March	87.1	209.6	142.6	286.4	138.0	92.7	147.3	192.6	106.6	246.0	212.4	87.7	162.4
April	36.6	252.0	101.8	123.5	92.4	81.2	136.5	132.6	89.1	139.5	144.9	56.7	115.6
May	39.4	232.5	68.2	112.2	73.2	54.9	77.5	86.5	84.6	328.1	124.0	58.9	111.7
June	31.8	147.7	44.3	47.2	33.8	52.9	60.5	62.5	67.4	111.0	115.0	32.2	67.2
Total	633.2	2508.0	992.4	1823.4	1069.2	707.1	1544.4	1273.7	985.8	1997.1	1276.7	841.3	1304.5

TABLE 3 TONS INSOLUBLE PER SQUARE MILE PER MONTH—COMPARISON OF 1923–1924 WITH 1912–1913[1]

	Stations											
	1		2		3		4		5		6	
Month	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13
August	35.7	36.0	204.8	144.0	56.1	36.5	135.8	85.0	126.8	116.6	28.7	59.6
September	44.2	36.3	219.5	140.7	66.6	47.7	144.4	65.9	111.4	107.2	35.7	59.7
October	51.8	45.0	269.7	156.7	91.1	54.5	214.5	101.8	84.9	150.9	57.7	81.1
November	56.7	17.1	213.0	215.1	95.7	32.2	197.7	71.3	93.0	126.1	77.7	70.6
December	115.3	45.0	264.7	210.2	106.0	85.7	170.5	159.5	108.5	123.7	82.5	130.0
January	70.4	41.7	220.7	146.2	125.5	66.5	170.5	208.5	123.1	92.3	82.8	89.4
February	64.2	33.7	273.8	173.2	94.5	66.0	220.7	149.0	84.1	122.3	60.3	66.6
March	87.1	50.5	209.6	151.9	142.6	48.8	286.4	191.4	138.0	109.2	92.7	64.3
April	36.6	124.1	252.0	142.6	101.8	68.0	123.5	172.9	92.4	179.6	81.2	136.5
May	39.4	35.2	232.5	115.8	68.2	29.1	112.2	169.3	73.2	192.1	54.9	28.5
June	31.8	83.2	147.7	159.6	44.3	68.8	47.2	158.7	33.8	130.6	52.9	117.5
Total	633.2	547.8	2508.0	1756.0	992.4	603.8	1823.4	1533.3	1069.2	1450.6	707.1	903.8

	Stations													
	7		8		9		10		11		12		Average	
Month	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13	'23–24	'12–13
August	110.2	66.1	143.9	71.5	57.5	56.4	140.8	37.2	70.2	66.1	34.8	39.5		
September	98.3	59.9	134.3	64.3	53.8	59.5	89.7	41.8	58.7	69.7	33.8	46.5		
October	68.8	67.7	78.1	102.7	158.4	54.2	188.7	58.3	98.9	96.1	181.4	50.7		
November	236.1	67.8	148.5	54.7	89.4	51.7	165.3	59.8	91.2	68.2	60.8	56.9		
December	233.7	93.5	62.0	46.8	94.2	139.5	248.3	120.7	88.0	139.6	83.4	82.1		
January	249.9	101.0	114.7	77.5	110.0	68.2	244.6	102.8	97.7	104.7	125.2	63.1		
February	125.6	29.9	118.0	46.1	74.8	41.6	95.1	46.2	175.7	94.5	86.4	40.6		
March	147.3	105.7	192.6	105.7	106.6	57.0	246.0	80.3	212.4	62.8	87.7	63.5		
April	136.5	38.7	132.6	81.9	89.1	59.3	139.5	43.7	144.9	84.9	56.7	52.4		
May	77.5	45.2	86.5	60.4	84.6	43.4	328.1	38.1	124.0	54.7	58.9	90.6		
June	60.5	70.0	62.5	104.3	67.4	60.7	111.0	44.8	115.0	65.8	32.2	42.9		
Total	1544.4	745.5	1273.7	815.9	985.8	691.5	1997.1	668.7	1276.7	907.1	841.3	628.8	1304.5	937.7

(39.1 per cent. increase)

[1] As no record was found of the areas of the containers used in 1912–1913, the total tonnage for a given station was taken and the average area calculated. This average area was used for each of the eleven months, which introduced an inaccuracy. However, no other method was available by which comparisons could be made.

TABLE 4 COMPARISON OF DEPOSITS IN THREE CITIES—TONS OF INSOLUBLE MATTER PER SQUARE MILE PER MONTH

City	Year	No. of stations averaged	April	May	June	July	Aug.	Sept.
Pittsburgh	1923–24	12	115.6	111.7	67.2	....	95.4	90.9
	1912	12	98.7	75.2	92.2	93.0	67.9	66.6
	1916	12	109.8[a]	212.5[b]	147.6	167.7	219.0[a]	167.6
St. Louis	1916	12	59.6	58.9	42.4	66.5	55.7	50.2
Cincinnati	1916	16	52.0	50.2	33.6[c]	49.2	33.9	....

[a] Average for 10 stations. [b] Average for 8 stations. [c] Average for 15 stations

Several instruments were tried, but no systematic study made, because there was no method of direct comparison with results of the previous investigation, which was the principal object of the second survey. However, sufficient data were secured to aid in the formulation of a program for further study of conditions.

SUMMARY AND CONCLUSIONS

Ordinances for the elimination of dense smoke are well worth while. It is possible to enforce fair regulations without undue hardship upon the manufacturer, and in a large majority of cases compliance has resulted in a material saving in fuel. *No plant has been driven from Pittsburgh through enforcement of the anti-smoke ordinance.*

Better results could be secured if cities were to employ larger forces of inspectors. Consider Pittsburgh, with nearly fifty square miles of territory to be covered by four men, with an annual budget for the bureau of about fifteen thousand dollars, including salaries.

Much has been done to educate plant owners that "Smoke Means Waste." Once an operator is convinced of this, it is comparatively easy to persuade him to make such changes in his plant as will admit of operation within the law. And boiler manufacturers are keeping step by perfecting smoke-preventing devices. It must be considered, however, that the problem is one of evolution, not revolution.

Only a small percentage (usually less than three per cent, and in Pittsburgh about one-fourth of one per cent in 1923–24) of the solid deposit consists of tar, which is the criterion of black smoke.

TABLE 5 ANALYSIS OF SAMPLES—AVERAGE PER SQUARE MILE BY MONTHS, AUGUST 1923–JUNE 1924

	Insoluble in Water										Soluble in Water								Included in Soluble		
	Tar		Fixed carbon		Ash[1]		Total		Fe_2O_3		Loss on ignition		Ash		Total		Per cent Insol.	Per cent Sol.	SO_3	Cl	NH_3
Month 1923	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%	Tons	%			Tons	Tons	Tons
Aug.	0.038	0.04	36.0	37.7	59.4	62.2	95.4	100.0	25.9	27.1											
Sept.	0.145	0.16	33.1	36.4	57.6	63.4	90.9		24.6	27.1											
Oct.	0.232	0.18	47.1	36.6	81.3	63.2	128.7		21.4	16.6											
Nov.	0.229	0.18	49.1	38.6	77.8	61.2	127.1		36.6	28.8											
Dec.	0.318	0.23	47.8	34.6	90.0	65.2	138.1		31.2	22.6											
1924																					
Jan.	0.202	0.14	51.3	35.5	93.1	64.4	144.6		16.8	11.6	3.18	21.2	11.83	79.8	15.01	100.0	90.6	9.4	6.96	1.67	0.916
Feb.	0.319	0.26	44.7	36.4	77.7	63.3	122.8		25.3	20.6	8.78	41.3	12.49	58.7	21.27		85.2	14.8	7.13	3.54	0.508
Mar.	0.390	0.24	54.1	33.3	108.0	66.5	162.4		36.1	22.2	9.74	29.8	22.94	70.2	32.68		82.7	17.3	12.29	2.29	0.784
Apr.	0.347	0.30	36.2	31.3	79.1	68.4	115.6		28.4	24.6	9.91	42.3	13.52	57.7	23.43		83.2	16.8	9.16	1.05	0.586
May	0.402	0.36	40.0	35.8	71.3	63.8	111.7		20.7	18.5	9.73	39.5	14.91	60.5	24.64		82.0	18.0	9.71	0.91	0.295
June	0.249	0.37	24.9	37.1	42.0	62.5	67.2		12.9	19.2	9.34	41.5	13.16	58.5	22.5		74.9	20.1	8.24	0.52	0.405
Total	2.87	0.22	464.3	35.6	837.3	64.2	1304.5	100.0	279.9	21.4	50.68	36.3	88.85	63.7	139.53	100.0	83.9	16.1	53.49	9.98	3.494

[1] Includes Fe_2O_3.

posit for Pittsburgh was higher than the average deposit for St. Louis and Cincinnati in 1916.

There was nothing in the data gathered in Pittsburgh in 1916 to indicate the reason for such an increase over 1912. It possibly was because of the fact that, as the Bureau of Smoke Regulation had just about been placed in full stride, efforts throughout the city to reduce the volume of dense smoke resulted in aggravating conditions in many cases before the remedy was found.

TABLE 6 COMPARISON—TAR, FIXED CARBON, ASH AND Fe_2O_3 IN TONS PER SQUARE MILE FOR ELEVEN MONTHS

	August–June 1912–1913		August–June 1923–1924	
	Tons per sq. mile	Per cent	Tons per sq. mile	Per cent
Tar	9.25	0.99	2.87	0.22
Fixed carbon	288.0	30.7	464.3	35.6
Ash[1]	640.5	68.3	837.3	64.2
Total	937.8	100.0	1304.5	100.0
Fe_2O_3	237.3	25.3	279.9	21.4

[1] Includes Fe_2O_3.

As stated previously, the insoluble matter was analyzed for tar, combustible other than tar, ash, and iron, and, beginning with January, 1924, for combustible, ash, sulphates, chlorine, and ammonia in the material soluble in water. The results are shown by percentages and by weights in tons per square mile.

A comparison between Pittsburgh August–June, 1923–1924, Pittsburgh August–June, 1912–1913, London (7 stations) August–June, 1922–1923 and London (7 stations) average of five years, is made in Table 7.

Table 8 is a comparison between Pittsburgh January–June, 1924, London January–June, 1922–1923, and London January–June, average of five years, both insoluble and soluble matter.

The data for London were obtained from the reports of the Advisory Committee on Air Pollution, published by the Meteorological Office of the Air Ministry.

The comparison shows that while in Pittsburgh there has been a material decrease in the tar content of deposited matter, with an increase in combustible other than tar and in ash, in London there has been little change in the tar content, in the combustible other than tar, or in the ash.

Further comparison between Pittsburgh and London shows less tar deposited per square mile in Pittsburgh than in London, but practically eight times as much combustible other than tar, more than six times as much ash in the insoluble matter, three times as much SO_3, and nearly twice as much ammonia.

The results thus far mentioned indicate the amount of solid matter deposited at a given place in a given time; equally important—probably more so from the standpoint of health—is to know the amount and character of solid matter in suspension.

TABLE 7 COMPARISON BETWEEN DIFFERENT PERIODS IN PITTSBURGH AND LONDON[1]

City	Period	No. of stations averaged	Insoluble Matter, Tons (2000 lb.) per Sq. Mi. Combustible other than tar	Tar	Ash	Fe_2O_3	Total
Pittsburgh	August to June 1923–24	12	2.87	464.3	557.4	279.9	1304.5
	August to June 1912–13	12	9.22	288.3	402.7	237.6	937.8
London	August to June average of 5 yrs.	7	3.54	56.6	134.4	...	194.6
	August to June 1922–23	7	3.37	59.8	116.8	...	180.0

[1] This comparison is made because of the completeness of the data reported for London and because similar procedures of collecting deposits were used in both cities. Otherwise the comparison is unfair to Pittsburgh, which is an industrial city that is confronted with more serious sources of air pollution than are encountered in London. It is unfortunate that similar data are not available for Sheffield or other English manufacturing centers.

It is said that in Duisburg, Germany, the deposits total 1200 tons per square mile per year.

For the month of June, 1924, the deposit in the center of Liverpool amounted to 97 tons per square mile. The average of the twelve stations in Pittsburgh for the same month was 89.7 tons per square mile.

TABLE 8 COMPARISON BETWEEN PITTSBURGH AND LONDON[a]

City	Period	Insoluble Matter: Combustible other than tar	Insoluble Matter: Tar	Insoluble Matter: Ash	Soluble Matter: Loss on ignition	Soluble Matter: Ash	Soluble Matter: Total solids	Included in Soluble Matter: Sulphates as SO_3	Included in Soluble Matter: Cl	Included in Soluble Matter: NH_3
Pittsburgh	Jan.-June 1924	1.91	251.2	471.2[b]	50.7	88.8	863.8	53.49	9.98	3.49
London	Jan.-June Average of 5 yrs.	1.98	32.4	77.7	30.7	55.3	198.1	29.93	10.56	1.84
London	Jan.-June 1922–23	1.97	34.1	71.2	20.9	47.2	175.3	17.51	10.66	1.81

[a] See footnote to Table 7. [b] Includes Fe_2O_3.

Yet this is the only part of the products of combustion which it is attempted to control. If a chimney is not emitting dense smoke it is considered to be a good chimney, regardless of the amount of coke, ash, iron, sulphur oxides, etc., it may be emitting. And which is the more harmful to fabrics, to buildings, to health? It will be worth while again to read over the summary of the effects of atmospheric impurities given early in this paper, and to note particularly what is said of the irritating effects upon mucous membrane and the predisposition to disease of the respiratory tract, especially pneumonia, the scourge of mankind, which annually levies a toll greater than that of all other infectious diseases combined. Surely the solution of the graver and more important part of the problem of air pollution is worth any effort and expense necessary. This solution lies in preventing any detrimental constituents in stack gases from reaching the atmosphere—they cannot be controlled after they have left the chimney.

Present Status of the Smoke Problem

By OSBORN MONNETT,[1] CHICAGO, ILL.

IN OUR middle-western cities there is gradually developing a realization of the character and magnitude of the problem of smoke abatement. For years the effort has been to provide suitable furnaces and boiler settings to insure minimum smoke production when properly operated. This work has been confined largely to the more important plants of industry, as this class of plant generally makes about half the smoke of any particular locality.

General improvement in design has been made, and there has been an evident desire for better settings. Manufacturers no longer insist on minimum headroom, but come forward voluntarily with setting heights that insure successful operation at high capacities.

Perhaps the most hopeful sign in general is the growing appreciation of the importance of air over the fire. Studies in the various strata of the fuel bed have shown how rapidly oxygen disappears and how utterly impossible it is to get a sufficiency of this medium to meet requirements without introducing it over the fire. This holds true not only with hand-fired furnaces, which have long been provided with some sort of air admission, but also in the mechanical-stoker field. Even chain-grate settings and underfeed stokers are now having air blown in over the fire by motor-driven blowers, increasing CO_2 content and all-round combustion efficiency, while preheated-air admission on powdered-coal installations is familiar to all engineers.

The vast quantities of rich hydrocarbon gases evolved on peak loads when using free-burning coal emphasizes the call for air, but of course, air at the right place and where temperature and mixture combine to complete the combustion.

The Real Problem Today the Small Heating Plant

The real problem today is the small heating plant. Little work has yet been done in the way of improving such plants, and in very few cases are there any regulations in effect governing their installation. Even ordinary precautions, such as smoke-pipe connections and chimney construction, which might have a good effect in obtaining better combustion, are practically neglected.

Efforts with this class of plant have been confined to using improved methods of firing. It is possible, by the application of simple firing methods, such as the coking or alternate method, to decrease the smoke density 75 per cent over the ordinary hit-or-miss method, and at the same time to increase the efficiency 15 or 20 per cent by decrease in the deposit of soot on heating surfaces.

Small heating plants are responsible for about 25 per cent of the total smoke in the heating season, and should receive a proportionate amount of attention. At the same time the relative importance of this class increases as progress is made with larger plants.

In Memphis, during a recent survey, a squad of high-school boys, without any previous experience, made an average reduction of 60 per cent in smoke density on a group of homes in which was installed a varied assortment of household equipment, which included open fireplaces, kitchen ranges, hot-air furnaces, round and square cast-iron boilers, stoves, and water heaters.

In other residence localities where educational methods have been tried, using student instructors calling on householders, the smoke has been reduced 50 per cent in the district.

Taking the smoke problem as a whole, we have, with mechanical stokers, powdered coal, coke, oil, manufactured gas, and producer gas, at least a theoretical solution for every problem confronting us. Yet with all this engineering development the smoke is still with us, and in most instances it is getting worse instead of better.

It is evident that there is more to the problem than well-worked-out engineering designs.

More Smoke Stopped by Diplomacy Than by Ordinance

There is the human element—the political aspect, the psychology of the business man who thinks he is being forced to do something. In this country it is not feasible to *make* any one do anything, any more than it is feasible to say that he *cannot* do certain things. We have familiar illustrations of the last proposition.

More smoke is stopped by diplomacy than by ordinance, and more frequently than not its abatement results incidentally from a general overhauling and modernization of the plant to *carry the load*, rather than from a deliberate outlay of money for this one object.

In cities almost entirely dependent on raw bituminous coal, with a large proportion of it being burned in comparatively crude apparatus, the human element becomes of prime importance. There is need for instruction; for organized, consistent, educational effort, for better equipment, and for supervision. This means that adequate smoke abatement is going to cost more than has been realized. None of the cities in the soft-coal districts have ever had sufficient appropriations really to cover the field.

No figure has been set as a standard for a satisfactory appropriation, but drawing from experience and observation in various campaigns in various parts of the country, it can be stated that a total expenditure of $50,000 a year per million of population is about the lowest estimate that will enable all phases of the subject to be handled with any degree of satisfaction.

This in effect constitutes an insurance rate of 0.3 per cent on the fuel loss and damage per capita to the community. Surely not a very high rate, although far in excess of the sum spent by most cities in this work. The above figures help to explain why, with all our engineering, we are not getting along faster with our smoke problem.

Importance of Supervision

Recent developments have emphasized the importance of supervision. After every one has been instructed and the necessary improvements in equipment have been made, it is imperative that a constant watch be maintained and a follow-up system installed, as otherwise the efforts are wasted. Firemen simply will not take the care required in operation of their furnaces, unless they know they are being watched.

Properly organized for the work, any city can expect to reduce smoke from all sources to such a point that it ceases to be a major nuisance. The smoke density of the various main divisions in unrestricted territories, together with the densities obtainable by intensive campaigns, and the possible percentage reduction, are shown as follows:

	Per cent of total problem	Unrestricted density, per cent	Highly restricted density, per cent	Per cent reduction possible
High-pressure industrial plants	45	40	2	95
Large heating plants	12	20	3	85
Railroads	18	49	6	85
Residences	25	10	4	60
Total	100			

This represents just about where we stand at present, and justifies a degree of optimism for the future. Efforts along present lines will bring about education. Education will bring a demand for better performance. This will be met by better equipment and methods in all classes of plant.

Fuel engineering is on the verge of big developments. These developments must come gradually, as public demand calls for them and as the economic situation fits into the scheme of things.

Future Possibilities

Looking into the future, it is not unreasonable to expect that prepared fuels will play an important part. Gas, the ideal fuel, will come into its own and complete gasification will find its application, especially where consumers are sufficiently concentrated to make distribution profitable.

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[1] Consulting Engineer.

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There will always be a large scattered fuel demand, which can be met best by solid fuel.

It would not be advisable to attempt to carbonize 500,000,000 tons of soft coal until the country was prepared to absorb the by-products. This question seems bound up with the problem of automotive-fuel supply, and the two may be worked out together to a happy solution.

One of the best features about carbonized fuel is that it would automatically solve the part of our smoke problem that is most difficult of control—the human element. Providing a foolproof fuel that could be shoveled helter-skelter into any kind of a fire pot without any precaution, would remove the last barrier to a realization of our dream of smokeless cities.

None of these things are going to come overnight. At the proper time, depending on economic conditions, the fuel interests and technologists will meet the situation. In the meantime we should not relax our efforts along present lines, as it is by these efforts that the field will be prepared for more radical measures.

Wood Finishing—A Glance Ahead

Wood Finishing as an Art, a Science, and a Branch of Engineering—Technical Knowledge of Wood the Foundation of Wood-Finishing Engineering—Need for Methods of Measuring Service Value of Finishes

By F. L. BROWNE,[1] MADISON, WIS.

FROM time immemorial the prophet has been granted a certain license in speculation, a certain freedom from the constraint of hard-and-fast detail, in order that the essential accuracy of his general forecast may not be too greatly obscured by petty discrepancies in particulars. Sufficient if the seer can predict the victor in the battle without setting forth in full the ebb and flow of the action; or, to change the simile, if he can foretell the direction of movement of the market during the next month without specifying, say, for the top quotation on Steel Common. In assuming the robe of soothsayer with respect to the future of wood finishing, then, the author bespeaks the traditional indulgence with regard to specific details in the hope that a consideration of general principles will be of interest and value at this time when wood-finishing practices are being subjected to critical scrutiny.

That wood-finishing methods are undergoing something of a revolution at the present time is obvious enough. The spray gun displaced the brush only a few years ago, and nitrocellulose lacquers challenged the supremacy of oleoresinous varnishes still more recently. Other new materials are being developed and still more radical changes in methods of application are likely to appear. But even more significant of the movement now under way is the fact that the A.S.M.E., in giving a special place on the program to the subject of wood finishing, recognizes that the time has come when certain phases of it, at least, must be placed under the charge of men having the specialized technical training of the engineer rather than be entrusted entirely to the craftsman.

However, in our enthusiasm to apply our technical knowledge to the solution of the wood-finishing problem we may make the serious blunder of thinking it a technical problem exclusively. It will be well to keep in mind that the technical aspect, though undoubtedly of primary importance, may prove in the long run to be more easily dealt with than other features. In fact, there are a goodly number of executives in the woodworking industries who would maintain that the problem is wholly one of foreman training, and that if one could find a satisfactory substitute for the old apprenticeship system, capable of providing craftsmen as competent as the good-old-timers are reputed to have been, there would be no need of calling in the aid of the technical man at all. So, before going to the other extreme, we should consider carefully how much of the burden of his finishing difficulties we dare promise to take from the executive's shoulders.

Wood Finishing as an Art

Wood finishing is at once an art, a craft, and a branch of engineering. It will always require skilled workmanship, esthetic appreciation, and technical knowledge. In the easy-going times when small manufacturing establishments were the order of the day, it was possible for the craftsman to assume the entire responsibility; but as the woodworking industries became more complex and more highly specialized the traditional policy of leaving it all to the finisher has been productive of more and more worry for the executive, until at the present time in many lines the finishing room probably gives rise to more exasperating difficulties than any other division of the operations. In looking for ways of improving the situation it is important to keep in mind that the problem has three sides, and that new developments on the technical side have an important bearing on the other two.

This is neither the place nor is the author the one to discuss the lines of future progress in wood finishing as an art. It is desirable, however, to emphasize the fact that the artistic consideration is a vital part of the wood-finishing problem, and that while it is likely to be affected by changes in technology, the engineer as such is not competent to advise upon it. The special talents of the artist, not always combined with those of the engineer or chemist, are required.

There are those who feel that the *art* of wood finishing has been even more seriously neglected than its technology, and that the tendency in recent years has been away from rather than in the direction of a better balance between these two aspects of the subject. At least two factors probably have tended to discourage artistic originality in wood finishing—the dominance of manufacturing considerations over esthetic values, and the craftsman's monopoly of finishing knowledge.

The first factor is well illustrated by the prevalence of very dark shades in walnut and mahogany furniture, dictated in all probability by the circumstance that it is easier to disguise birch and gum in combination with the more expensive woods when such finishes are employed than when using the more attractive lighter shades. When fashion swung to the other extreme during the recent vogue of French walnut, the attempt to use the darker-colored wood by bleaching led to a good deal of trouble and produced some finishes that left a good deal to be desired from the point of view of beauty.

The importance of the second factor tending to discourage artistic originality in wood finishing is manifest. Since the craftsman is concerned primarily with the routine of production, he naturally tends toward standardizing his work with as few materials and operations as possible, and opposing the introduction of new effects and new technic. For obvious reasons he is likely to take sides with the engineer against the designer in the conflict between convenient production and artistic expression. When he alone possesses the knowledge of what can be done in the way of finishing and how to do it, as has been the case all too frequently in the woodworking industries, the designer's efforts are very narrowly circumscribed. It is much like asking an artist to paint with three or four prepared paints of unknown composition which he is forbidden to mix or alter in any way. A talented artist no doubt could produce an excellent picture, but he will probably turn to a more flexible vehicle for expression. Similarly, higher standards of beauty in wood finishing are not likely to be achieved until the designer is freed from thraldom to the craftsman. To produce that result the technical man will have to devise adequate means of measuring the adaptability of the available materials and describing the results with different procedures. The choosing of proper finishing operations and the selection of necessary materials is then properly as much a part of design as the specifications for the woods and dimensions of the various parts.

There are, as a matter of fact, signs of a rebellion against mediocrity in wood finishes. As the lumber associations improve their merchandising methods they are emphasizing the finishing possibilities of their woods. The mahogany and walnut interests urge shades that bring out the beauty of their woods more clearly, the groups interested in maple are centering their advertising upon the new light brown and gray finishes for it, the gum producers would like to popularize distinctive finishes, and even some of the softwood interests are devoting much attention to the development of appropriate finishes. Now that the radio is competing with the automobile for the attention of the public, it seems reasonable to suppose that people will again be at home enough to heed the broadcast clamor of the lumbermen and demand beauty in the finish of their furniture and woodwork even as they do in their cars!

[1] Chemist, U. S. Forest Products Laboratory.

Contributed by the Wood Industries Division for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of The American Society of Mechanical Engineers. All papers are subject to revision.

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WOOD FINISHING AS A CRAFT

The wood-finishing craftsman has been traditionally jealous of the intrusion of the uninitiated, especially the engineer and chemist, into his secrets, and the technical man in return has continually increased the complexity of the subject by perforce introducing new materials, new methods of application, and even new woods, each departure from the good old-fashioned way bringing with it a whole new set of special precautions to be learned if disaster is to be avoided. Unfortunately, that rivalry has resulted in placing altogether too much emphasis upon cook-book formulas of magic concoctions. Both craftsman and chemist have wasted too much time in the vain search for a philosopher's stone of wood finishing. As a matter of fact, to obtain a given effect there are usually a dozen different methods, any one of which will give excellent results if skilfully applied, but no one of which will produce a really first-class job unless handled with skill and good judgment.

The craftsman's place in wood finishing is assured not by the secret formulas which he thinks he possesses but by his mastery of the materials with which he works. Technical progress has a way of making more rather than less demand upon his ability. It is more difficult to apply smooth, uniform coats by means of the spray gun than with the brush, and the care and operation of the new tool are more intricate. Nitrocellulose lacquers are even more capricious than varnish, and require closer attention to avoid getting into trouble. Not only are the newer materials and methods increasingly complex, but their very multitude in itself adds to the craftsman's burden by making it necessary for him to familiarize himself with the peculiarities of many different products. A generation ago the finisher needed to understand the use of a few dozen materials, whereas today he must be able to handle several score.

While the demands upon the craftsman have been growing more exacting, social forces too familiar to need mention here have combined to make it more difficult for industry to obtain skilful wood finishers in sufficient numbers. Much attention has been paid to the problem of finding a satisfactory substitute for the obsolete apprenticeship system, but thus far without much success. There seems to be a tendency for the woodworking industries to look for help from outside—from the schools or even from governmental bureaus—but it seems to the author that the problem is such a vital one to industry that its solution must be sought from within. Even with the excellent training in engineering subjects now furnished by the universities, some industries find it worth while to provide their own special schools for graduates entering their employ. But whatever the answer to this question may be, it is sufficient for present purposes to recognize that the training of craftsmen is a major portion of the wood-finishing problem which is not likely to be solved by developments of a purely technical nature but on the contrary may be rendered more acute.

WOOD FINISHING AS A BRANCH OF ENGINEERING

Although the engineer is not the only expert whose special talents will be required to solve the wood-finishing problem, there can be no question that he must be called upon for an exceedingly important contribution.

It so happens that the technical man whose attention is drawn to wood finishing is very likely to approach the subject from the direction of the paint and varnish industries rather than from the side of the woodworker, and therefore to look upon wood finishing as a branch of paint science. The reason is not far to seek. Wood-finishing materials are commonly regarded as "chemicals" requiring the special knowledge of the chemist to understand them; the chemist, although sometimes thus enlisted in the paint and varnish industries, is practically unknown in woodworking. As there are plenty of unsolved problems in the chemistry of paint and varnish to keep the technical men of that industry too busy to learn about wood, the development of such technical knowledge of wood finishing as now exists has been decidedly one-sided.

As a matter of fact, wood-finishing engineering should have its foundation in wood science rather than in paint science. Complicated and imperfectly understood as our finishing materials are, the wood is still more complex and even less understood. Troubles in wood finishing probably arise far more often as a result of the peculiarities of wood than of those of the finishing materials. The characteristics of wood can be controlled only within very narrow limits, and as timber supplies become less abundant it is more difficult to choose woods for their ease of finishing alone. The finishing materials, on the other hand, are nearly all manufactured products or could be replaced by manufactured products, and therefore can be altered more nearly at will to suit conditions imposed by the wood. The ideal in wood finishing, therefore, is most likely to be achieved when we start with a thorough knowledge of wood properties and select materials and methods in conformity with them rather than by trying to modify wood properties to suit finishing methods.

If wood science is the foundation of wood-finishing engineering, then the latter is surely in its infancy, for our technical knowledge of wood is woefully inadequate. Long accustomed to dealing with wood, the average man does not realize how little is really known about it. Incorrect explanations of common observations and even statements of "facts" that are "not so" are accepted without question by engineers and chemists as well as by laymen. Hawley[2] has exposed a group of such fallacies. His list is representative, not exhaustive. Even such an apparently simple question as "how does moisture escape from a piece of wood during drying?" cannot be answered satisfactorily at the present time.[3] The obviously incorrect statement that the shrinkage of wood during drying is due to the removal of free water from the "pores" of the wood appears in print with discouraging regularity. Until we are in a frame of mind to answer such questions less glibly and more thoughtfully, it will be inopportune to try to explain such interesting facts of wood finishing as:

1 The effectiveness of shellac as an undercoat in comparison with other spirit varnishes, oil varnishes, and lacquers.

2 The difference in the amount of dyestuff required to stain wood a given color with a water or alcohol stain and with an oil stain.

3 The lighter color given to the summerwood of a softwood as compared with the springwood when using an oil stain, despite the apparently deeper penetration into the summerwood.

4 The property of a wood which the finisher calls "suction" and the paint technologist calls "absorption," and which seems to bear no relation to the ease with which the wood can be impregnated with chemicals.

5 The ease with which some oils and resins in woods work their way through paint and varnish coatings, apparently without rupturing them.

6 The development of such exasperating finishing-room troubles as varnish "shrinkage," "pinholing," and "blooming."

7 The apparent development of a third dimension or "depth" in a wood surface when shellacked, varnished, or lacquered.

Spectacular developments such as the widespread adoption of lacquer during the last few years are likely to mislead us into thinking that the important technical advances in wood finishing are to be sought in radically new materials and new methods. Undoubtedly many valuable new inventions will be made as the subject of wood finishing receives more adequate technical study, but it is the author's belief that even more profitable results can be expected from the better utilization of existing methods and materials which will result from a painstaking study of the fundamentals. Already there is a vast accumulation of empirical knowledge, much of it rendered mysterious by an overgrowth of fanciful theory. If the information is subjected to the cold scrutiny of systematic research and every theory examined with a vigorous skepticism, it should be possible to separate facts from fancies and to organize a body of knowledge that will form the real basis of a wood-finishing engineering.

One of the first problems for the future in wood-finishing engineering is the development of tests for *measuring* results. This is practically a virgin field, because heretofore very little has been accomplished except to finish sample panels and pass judgment upon them by visual inspection. For example, such a property of a varnished surface as "depth" should be susceptible of measurement by a suitable instrument. The trained eye of the ex-

[2] Seventeen Fallacies about Wood, News Edition of *Industrial and Engineering Chemistry*, vol. 3, no. 15, Aug. 10, 1925, p. 5.

[3] See The Movement of Moisture with Reference to Timber Seasoning, (British) Forest Products Research Technical Paper No. 1.

perienced finisher seems to be very sensitive to it, but a mechanical "eye" of some kind is essential for a technical study of the property. With proper tools at his command for measuring this and every other significant factor, the engineer would be in a position to determine precisely how much each step and each variation contributes to or detracts from the finishing process as a whole.

The need of adequate tests for evaluating finishes will probably be felt most keenly in its relation to the selection of finishing materials. Every purchaser of such products has realized the difficulty in choosing intelligently among the many brands offered to him. Usually price and the reputation of the manufacturer are taken as the only available index of quality, and the most common method of testing is the hazardous one of using a trial shipment. Attempts to adopt other test methods as the basis of selection have been made often enough but have usually proved abortive.

Trying to borrow the test methods of the chemists of the paint and varnish industries is the most common reason for the failure of the woodworker's efforts to test materials. The varnish chemist, for example, finds a viscosity test very useful as a routine method of control of the uniformity of successive batches of the same varnish; but it does not follow that the viscosity test alone will tell the purchaser which one of several varnishes is most suitable for his use. Again, there is a natural tendency toward the assumption that a chemical analysis of a material gives all necessary information about it. But when the consumer tries to purchase finishing materials on the basis of a chemical analysis he finds himself at once at loggerheads with the makers on the ground that he is attempting an unwarranted intrusion into their trade secrets. Whether the varnish-makers' argument is valid or not, the woodworker will usually find that knowing the formula of a material will not help him much in determining what it will do.

Manufacturers of wood-finishing materials in the past have not found it necessary to devise methods of measuring the service value of their products, and they are not likely to spend much time in that direction unless the woodworkers themselves lead the way. The author recalls the experience of one large factory which was greatly troubled with varnish printing during shipment of their furniture. The problem was turned over to an engineer who soon devised a test requiring no more elaborate apparatus than some wood panels, some kraft paper, a few weights, and a corner of the factory cellar where temperature and humidity remained constant. When purchases of varnish were made in accordance with the findings of this test the printing troubles were eliminated. It is true that much more time and ingenuity will be required to work out practicable testing systems covering all the requirements of many finishing materials, but where a serious effort is made to do so it is likely to be generously rewarded.

The Use of Wood Lacquer Finishes

Particulars Regarding the Preparation of Wood Surfaces for Finishing, and Methods of Applying Pyroxylin Lacquers That Have Proved Successful in Practice

By WALTER S. EDGAR,[1] NEWARK, N. J.

PERHAPS the most noticeable trend today in modern industry is that looking toward the elimination of rule-of-thumb methods by substituting scientific research and control. The success achieved by the leaders in such industries as the oil and electric has had its influence on other trades with which we do not usually associate research. Twenty-five or fifty years ago we were in the age of invention, which was shortly followed by that of scientific control of labor operations. Today we are in the age of research and the improvement of already existing processes. Outstanding among the industries so affected by this movement is that of making protective and ornamental coatings, which had no noticeable change from the introduction of wood oil twenty-five years ago until the introduction of the pyroxylin lacquer. The difference between the modern lacquer and that of ten years ago lies largely in the amount of pyroxylin present. One thing of note in the present development of many products is the use of old facts or discoveries for the production of modern materials. Practically all of the principles now being used in the preparation of the lacquer of today have been known for many years. Plasticizers, for instance, which are considered so important in formulating, were discovered about sixty years ago.

Finishing materials fall naturally into three general classes. Class I consists of those which dry entirely through chemical changes, and includes such materials as portland cement, plaster, etc. Class II consists of those materials which dry by evaporation of the solvent that carries the solid or solids of which the final coating consists. The fundamental difference between classes I and II is that after those of class I have dried they cannot be brought back to their original condition, while those of class II may be brought back by the addition of the same solvents which were used in manufacturing them. This second class includes such materials as shellac, shellac substitutes, and wood lacquers. Class III consists of the familiar varnishes or oleoresinous compounds which might be considered as a combination of the first and second classes. These compounds are made by dissolving fossil resins, or what are more popularly called varnish gums, after they are fused in some type of vegetable oil, to which mixture are added thinners or extenders. With such finishes the first reaction is an evaporation of the solvents, which gives the initial set, and after this the oxidation of the vegetable oils, which oils furnish the toughness and durability to the finished coating. This oxidation changes entirely the character of the oil, and consequently of the coating, and it cannot be brought back to its original condition.

Pyroxylin as a Binder

All wood-finishing materials are built around some type of binder which should be hard, elastic, and durable. In the lacquer type of finishing materials the binder is known as pyroxylin or nitrated cotton. This is a stable chemical compound and as such is a better binder than a drying oil, which through oxidation changes progressively, and where the oxidation is made too rapidly because of the method of manufacture, the finish is injured by the "burning" of the oil. The particular point to bear in mind is that as soon as the solvents have evaporated from a lacquer, leaving on the surface a pyroxylin binder, a permanent, hard, elastic finish is produced which undergoes no chemical change causing deterioration. On the other hand, an oleoresinous finish is subject to progressive change and deterioration through oxidation.

Pyroxylin is made by treating linters, which are the short fibers of cotton closest to the seed, with a mixture of acids, principally nitric. The average amount of nitration is 12 per cent, and it is vitally important to control this to the fraction of a per cent to obtain uniform results in the various types of lacquers. After these cotton linters have been so treated they become soluble in a large number of solvents, and the degree of solubility of nitrocellulose in various solvents and under various conditions is one of the important things that the users of these finishes should learn. Fortunately none of the solvents generally used is injurious to health. This nitrated cotton is white and somewhat fluffy. Sometimes it may have been noticed that the lacquer has whitened when drying. This effect is caused by the actual precipitation of the cotton in the lacquer, brought about by the presence of too much of a liquid which is not a solvent for cotton, such as water.

Various ingredients are added to the binder for the properties which they possess: gums for adhesion, gloss, and ease of rubbing, and to increase the solid content; pigment for color effect. As in varnish, the apparent consistency of the material is no real indication of the total amount of solids present. Two solutions of the same viscosity may vary from 10 to 15 per cent in solids, due to the difference in the binder or the different way in which the binder is thinned.

Preparation of the Wood Surface for Finishing

Starting with the glues, we may note what may happen with the various types and the effect they may have on the lacquer coating. There are two general classes of glue now in common use: namely, vegetable glue and animal glue. A vegetable glue is somewhat cheaper, can be more easily handled by skilled help, and does not dry as quickly as animal glue. If a vegetable glue is used with lacquer some care should be taken to note that it is entirely dry before the first coat of lacquer is applied, and that an excessive amount of caustic has not been used in its preparation. This caustic would retain the water and act on the nitro-cotton, producing a white cast. Under these circumstances the author would recommend the use of animal glue.

After the veneer has been prepared, extra care should be used in the sanding. Lacquer does not fill as well as varnish because of its speed of drying, therefore the amount of extra labor spent on the preparation of the surface is well repaid by the results obtained and material saved.

Staining. The wood is now ready for staining. Water stains should be used as they are less soluble in the solvents used in lacquer than are either spirit or oil stains, and there is less probability of their coming to the surface where the action of the sun's rays will bleach or discolor them.

After the wood has been stained it should be allowed to dry at least 24 hours before commencing the filling operation.

Filling. It is now generally conceded that the best and cheapest practice is to give the wood a wash coat of either shellac or lacquer, followed by a light sanding before filling. This method not only gives a better and smoother foundation for succeeding coats, but prevents the binder in the filler from being absorbed by any spongy or soft veneer and also prevents the filler from turning gray or white. It generally saves a coat of varnish or lacquer and prevents not only trouble with the filler, but shrinkage of the finish as well.

Reasons Why Fillers Bleach

One of the great cries against lacquer is that it bleaches the filler. This is never so under reasonably fair conditions. Bleaching the filler is due to one of three causes.

First, the filler may be applied in a very dry condition, and if it is not packed into the pores of the wood there is an initial swelling when the lacquer is applied. In a short time this settles down, pulling the lacquer away from each pore, which by light refraction shows "white." The remedy is obvious: all filler should be applied in as heavy a condition as possible and rubbed in, and on work which is to be of extra quality a double filling operation should be made.

Second, another cause of bleaching may be the fact that soluble

[1] Flood & Conklin Co., Varnish Makers.

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colors were used in the preparation of the filler. As the lacquer is applied the solvents dissolve these oil colors and bring them to the top, leaving nothing but the oil and silex, which naturally produces a gray cast.

Third, still another cause may be the use of too much turpentine substitutes and naphtha. This material staying in the filler attacks the under side of the lacquer, and again we have the well-known condition of precipitation, producing a grayish cast.

Generally speaking, the filler that is used should not be too short and should not dry with a gray cast. If such a filler is being used the conditions may be corrected by the addition of oil and japan drier, turpentine being used as a thinning agent.

SPRAYING—BLOOMING TROUBLES

After the filler has dried for at least 48 hours and has been rubbed and sanded, care being taken that there is no smear on the work, it is then ready for the spraying. The first trouble from spraying is entrapped air and the remedy for this is quite obvious. Either the lacquer should be thinned or the air pressure should be raised so that the lacquer may be better atomized. An extreme condition of this type will result in the lacquer going on too dry, causing so-called "spray dust" and the same remedy should be taken. Bridging over moldings, etc. also results from substantially the same condition.

Lacquers during very humid weather sometimes show a bloom. What happens when a lacquer blooms may be readily understood by remembering the process for the manufacture of artificial ice. Wherever we have a liquid which is expanding to a gas, a large amount of heat is taken up from the surrounding atmosphere, the temperature is naturally lowered, the dewpoint is reached, water is deposited on the lacquer surface, remains there after the solvents have evaporated and again we have our familiar white appearance due to the throwing out of the cotton by the non-solvent. Two remedies may be used to overcome this condition. First, the lacquer may be made slow-drying enough to bring the rate of evaporation to that point where the temperature is not severely affected, or in the event that water does enter into the lacquer film, it will pass off before all of the solvents evaporate. These slow-drying solvents, unfortunately, are the most expensive ones, and it is more economical for a consumer to carry in stock a material usually called a "retarder." This may be added to the lacquer on those days when the relative humidity is high, and when this blooming trouble might be expected to appear. Second, certain very simple chemical means may be taken to help this condition. A number of lacquer consumers are now placing shallow pans containing calcium chloride in their spray rooms. It is also oftentimes helpful to heat the air, which naturally reduces the humidity.

RUBBING AND PATCHING

After the lacquer has been sprayed and dried, it is ready for the rubbing and patching. The time which should elapse between successive coats of lacquer depends largely on the type of lacquer and the kind of work being finished. Usually the best results are obtained by applying only one coat of lacquer each day and rubbing after 24 hours. This method helps to prevent shrinkage.

Generally speaking, it is possible to spray coats of the average type of lacquer about four to eight hours apart. Some lacquers give the best condition for rubbing after having stood for about 40 hours. Others should be rubbed after standing over night. It will need some experimenting under the conditions in each particular plant, as well as the recommendation of the man who is offering the material to determine the best schedule for coating and rubbing. Most furniture manufacturers prefer an oil for rubbing, since it saves one operation. The author prefers water, or if this not possible, then a debloomed oil.

The grayish cast which comes on the lacquer surface after it has been oil-rubbed may come from two causes: First, the lacquer may have been rubbed too quickly or too severely, and some of the pumice which was used may have been ground into the surface; then, as the rubbing vehicle dries out the pumice comes back to its original color, producing a grayish, spotty cast over the surface of the work. To overcome this condition, a fine pumice should be used, allowing the work to dry for two days before rubbing. Second, the grayish cast may also be due to the neglect of the finisher to thoroughly clean off the oil from the surface. This oil penetrates the lacquer finish and since oil is not a solvent for pyroxylin, it precipitates the cotton and produces our familiar gray.

Those places which have been rubbed through should not be touched up with alcohol or shellac, as would usually be done with varnish, but a lacquer toner should be prepared. This is made in the same manner and applied in the same way as colored shellac.

It will be noted throughout the entire consideration of lacquer, that this relation of solvent to pyroxylin stands out as the one thing to be remembered. Lacquer has been so widely advertised as a quick finish that there is a grave possibility it will be abused in this respect and that there will be a tendency to rush it too fast.

If it were possible to secure the adhesion, filling, and easy rubbing that is necessary to produce a satisfactory finish on wood with pure nitrocellulose, the finish would be practically indestructible. While lacquer gives a particularly tough and hard finish, it does not compare favorably with the oil products as far as distensibility is concerned. A pure nitrocellulose film of the usual commercial low-viscosity type, suitable for use in a wood lacquer, has comparatively little flexibility, and it has been found necessary to add extremely slow-drying solvents known as plasticizers so that the solution theoretically will never dry. This tends to add materially to its distensibility. One of the characteristics of nitrocellulose is its failure in a clear film under sunlight exposure. Among the investigations which have been made is that of the absorption of the ultra-violet light by nitrocellulose and vegetable-oil films, in which it is clearly shown that nitrocellulose films do not absorb as large an amount as the vegetable-oil, but that the effect of the smaller amount of rays absorbed is greater on the nitrocellulose film than on the vegetable-oil film. Furthermore the structure of nitrocellulose has been likened to an inverted pyramid, in which the slightest change on the point produces a rapid and accumulative deterioration. The problem in this case would seem to be one of finding a suitable stabilizer which would prevent this first reaction. Most of the stabilizers now used for that purpose either have an objectionable color or are not active enough to accomplish results desired.

When automobile lacquer enamels were first prepared very little thought was given to the selection of the pigment. Generally the pigment which gave the color desired was selected with often times very disastrous results. At the present time it is quite generally known what pigments should be used with lacquer coating to secure the most satisfactory results. The question which comes to most minds in considering the relation of the binder to the coating material, is why any number of hard, durable materials cannot be used for coating. There are a great number of compounds which are known to be durable and to give a satisfactory appearance, and it would naturally seem that they should be commercially practical. Almost without exception, however, these have the disadvantage of not drying quickly from solution. If we could produce a material which dried by a combination of chemical changes and evaporation, one in which we could control the rate of chemical change, we should be approximately at the point of having an ideal coating material. Such a material should produce a glossy, good-filling and adhesive material, which when sprayed upon the work would so change that succeeding coats would not attack it. It would be a material which would be practically 100 per cent film, reducing the cost materially.

Considering the plans which the formulator of coating material has in mind, the possibilities of using a long range of materials, there can be no doubt that the problem will be more quickly solved if there is the closest coöperation between the man who is manufacturing the material and the man who is to apply it. The history of the modern lacquer industry shows very clearly that more than half of the problems in their use are connected very closely with methods of application. Much of the success in the automotive field is undoubtedly due to the desire on the part of the lacquer man to meet the conditions which have been laid out for him rather than to attempt to make the conditions meet his formulating. Certainly, unless there is a broad understanding between the manufacturer and the consumer, with a good understanding on the part of the man who is directly concerned with the application, there can be no progress, but such coöperation, when it comes about, as no doubt it will in the near future, will unquestionably result in the development of the ideal coating material.

A Study of Varnish and Lacquer Finishes Exposed to Accelerated Breakdown Tests

Results of Comparative Tests on Wood Blocks Coated with Varnish and with Pyroxylin-Base Lacquer, and Conclusions Drawn Therefrom

By PAUL S. KENNEDY,[1] NEWARK, N. J.

THE prominence into which the nitrocellulose-base or so-called lacquer finish has recently come has caused speculation as to its value in service as compared with varnish finish on wood.

Regardless of the claims made in good faith for lacquer, at least four factors must be given consideration:

1 The General-Ignorance Factor. Extravagant claims spread by extensive advertising and propaganda, and backed up by admittedly successful improvements in automobile finishing, have led many to accept motor-car-finish results as a criterion for all other surfaces to be finished.

2 The Surface Factor. There is a vast difference physically between wood and metal.

3 The Manufacturing Factor. In industrial finishing local and economic conditions govern to the extent that the customer is frequently not furnished the material he *should* use, but what he *must* use to meet those conditions.

4 The "Enthusiasm" Factor. Time and experience are vital in determining finish facts. Practical experience over a period of time is admittedly missing with the use of lacquer on wood.

That these factors are not more generally appreciated is to be regretted.

May the author now declare himself as a nitrocellulose-finish enthusiast? He believes in wonderful possibilities for it and has directed his energies in that direction since the moment lacquer was first whispered of as a possible automobile finish.

But the engineer knows his feelings subsequent to the marketing of a brand-new proposition. His sales department must have enthusiasm and absolute belief, but in the back of his mind he is waiting for that conviction to materialize.

As a matter of fact, a failure secured with humidity in some hours on a lacquer film was checked up in actual production and afforded a positive solution to a new and disturbing deviltry, the cause of which might otherwise have remained somewhat in doubt; at least for a long period.

The idea of this general investigation was to determine the relative periods of finish "breakdown" under different systems of finishing and to find what would be the eventual appearance of the failures.

TABLE 1 RESULTS OF ACCELERATED BREAKDOWN TESTS OF VARNISHED AND LACQUERED WOOD SURFACES

WS—Water stain
SS—Swab coat of shellac
MF—Mineral paste filler
S—Shellac
L—Lacquer
V—Varnish
AS—Alcohol or spirit stain
OS—Oil stain
PSF—Pyroxylin combination stain and filler
I—Insulating varnish coat
G—Presence of glue on wood surface

Panel set	First coat	Second coat	Third coat	Fourth coat	Fifth coat	Sixth coat	Seventh coat	Eighth coat	Cross-cracks per inch	Predominating cracks	Blistering	Rating
1	WS	SS	MF	S	L	V	V	..	38	A	1	3
2	WS	SS	MF	S	S	L	V	V	34	T	0	3
3	WS	SS	MF	L	V	V	..	..	41	T	3	3
4	WS	SS	MF	L	L	V	..	..	38	H	0	2
5	WS	SS	MF	V	V	V	..	..	48	T	0	5
6	WS	SS	MF	L	L	L	..	..	32	A	0	1
7	AS	MF	S	L	V	V	V	..	25	A	2	3
8	AS	MF	S	S	L	V	V	..	28	T	2	2
9	AS	MF	L	V	V	..	..	..	32	T	2	3
10	AS	MF	L	L	V	..	..	..	32	H	0	2
11	AS	MF	V	V	V	..	..	..	22	A	0	3
12	AS	MF	L	L	L	..	..	..	48	H	0	1
13	OS	MF	S	S	L	V	V	..	32	A	1	3
14	OS	MF	S	S	S	L	V	..	35	T	5	3
15	OS	MF	S	L	V	V	..	..	16	T	3	3
16	OS	MF	S	L	L	V	..	..	44	T	4	3
17	OS	MF	S	V	V	V	..	..	20	T	1	3
18	OS	MF	S	L	L	L	..	..	38	H	0	1
19	PSF	S	L	V	V	..	..	..	25	T	4	3
20	PSF	I	L	V	V	..	..	..	48	T	2	3
21	PSF	L	V	V	..	..	..	..	41	T	0	4
22	PSF	L	L	V	..	..	..	..	51	T	0	3
23	PSF	V	V	V	..	..	..	..	20	T	0	4
24	PSF	L	L	L	..	..	..	..	51	H	0	1
25	WS	SS	MF	I	L	V	V	..	40	H	3	3
26	WS	SS	MF	I	L	L	V	..	51	A	0	2
27	WS	SS	MF	I	L	L	L	..	48	H	2	1
28	WS	SS	MF	I	V	V	V	..	38	T	2	4
29	PSF	I	V	V	..	..	..	..	38	A	1	4
30	G	WS	SS	MF	V	V	..	..	10	A	0	2
31	G	WS	SS	MF	L	L	..	..	48	A	5	0
32	G	PSF	L	L	..	..	..	..	38	A	0	0

An Accelerated-Weather Investigation of Wood Finishes

The author is now most interested in the "enthusiasm" factor, and solely from the standpoint of its fundamental, educational, and improvement value.

With this in mind, he has conducted an investigation with a so-called accelerated-weather apparatus consisting of artificial sunlight and rain and freezing tanks, giving any cycle of weather conditions desired. The rain tank, however, was not employed in this study.

The light tank reproduces the intensified finish-destroying ultra-violet rays of sunlight by means of a special Cooper-Hewitt mercury lamp, together with adjustable conditions of temperature and humidity. The freezing tank is fitted with an automatic refrigerating machine especially designed for uniform testing, temperature reading, and regulation.

Both shortness of time and the fact that this apparatus was working at top capacity on routine testing have limited the results obtained in this effort to anticipate what actual normal service results would be by artifically producing finish breakdown in a comparatively brief period.

Admitting that this work is open to criticism on many counts, it at least affords the basis for some interesting surmises made possible after *days*, instead of *months*, or even *years* of experience.

The varnish used in this test was a popular piano and furniture grade of medium elasticity—typical of the kind employed for a good "satin finish." The lacquer used was typical of a good piano and furniture grade designed to meet the "building" and rubbing and polishing requirements of production. The pyroxylin-base stain and filler used was a single-application product, as its name implies. The other products were all typical of good materials used in finishing practice.

The tests were run on solid mahogany panels of a size practical for our particular testing purpose and in the case of three of them, some glue was deliberately applied to duplicate the condition of poorly-cleaned-off veneer work.

Incidentally, enough checking with veneer and solid wood has subsequently been done to indicate no appreciable difference in the performance of the woods themselves.

All panels received extra protection at end-grain points.

The exposure of the panels consumed 205 hours of light and 25 hours of refrigeration, divided into approximate periods of 20 hours and two hours, respectively.

The maximum temperature at any time during the run was 120 deg. fahr., and the average relative humidity, 0.75.

These conditions are abnormally severe for wood, and such as to destroy the possibility of accurate determinations as to the progress of finish breakdown. The intent, however, was to secure relative destruction comparisons, and with suitable time available the experiments would be repeated under less abnormal conditions.

[1] Vice-President, Murphy Varnish Co.

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Panels were given a microscopic examination after each run and the final results are shown in the accompanying table, which also outlines the method of finish employed.

The "cross-cracks per inch" column gives an average figure of the number of temperature cracks the panels showed. A high crack number does not necessarily mean a bad endpoint as to appearance, as in some instances of comparatively lower crack numbers the cracks, though few, were wide and deep, showing destroyed protection.

Three kinds of checks showed up: temperature or "cross-grain cracks," denoted by *T* in the column "Predominating Checks:" humidity or "with-the-grain cracks," denoted by *H*, and old-age, similar to "overcoating cracks," denoted by *A*.

Many of the panels blistered. The numeral 5 denotes the most blistering and 0 no blistering.

In the last or rating column, the panels were graded according to final general appearance, the numeral 5 indicating the best and 0 the worst.

Summary of Results Obtained

The following is a brief summary of interesting points brought out during the course of this test:

1 On straight lacquer finish, humidity or "grain-swelling cracks" predominate.

2 On varnish finish, temperature or "cold cracks" predominate.

3 Wherever shellac was used under the finish, either old-age or temperature cracks predominated.

4 Cold checks were more pronounced and closer together when water stain was used. Pyroxylin-base stain and filler ranked next. Panels stained with oil and spirit stains had the least number of cold checks.

5 Cracks were less pronounced with varnish than with lacquer, and the combination finish of varnish and lacquer bore this out, two coats of varnish over lacquer being better than one coat, etc.

6 Generally speaking, two coats of varnish over lacquer gave a good average result.

7 The finishes tested with pyroxylin-base stain and filler as a group ranked most consistent for final appearance, particularly from the standpoint of lack of grayness or deadness.

8 In the course of testing, the first failures to appear were the humidity cracks in lacquer.

9 Once lacquer finishes cracked, they showed little of the property, common to the varnish, of "closing up" upon return to normal conditions.

10 Glue on the surface of wood is very dangerous. A milky condition produced disappears on exposure to ultra-violet rays, but pronounced "gold blisters" are produced under lacquer. Varnish showed more resistance to glue beneath it than lacquer. The two lacquer panels with glue on wood surface showed up the worst of the entire set.

Consulted as to the question of the severe humidity checking of the lacquer finish, a member of the staff of the Forest Products Laboratory of Madison, Wis., stated that when an unfinished wood panel was exposed to moisture it started to crack first with the grain, and as deterioration continued, crowfeet cracks appeared.

The conclusion is that the lacquer, being less distensible than varnish, has broken down under the influence of humidity, which produces the wood cracks just mentioned, and they transmit themselves in form and appearance as in the failure on this investigation.

3 The "built-up" lacquer finish so often now demanded to replace varnish finish requires the addition of solids which are brittle in comparison with the elastic nitrocellulose. The latter unfortunately neither builds nor rubs easily. Generally speaking the ideal properties of nitrocellulose are in direct proportion to this "adulteration." On the other hand, the manufacturer must give his men a full finish which they can rub to surface with reasonable physical effort, and this is a governing workshop fact.

4 The strongest argument for lacquer for wood finishing at the present time is its resistance to humidity checking, even in the factory during dog days. The more elastic the lacquer, the more its resistance to the absorption of humidity through the film proper, and consequently the less the chance for "grain swell." On wood the present best solution of the problem appears to be the use of an elastic lacquer which does not have to be rubbed to a discriminating surface, or the use of such a lacquer to coat up with for speed and apply final coats of varnish which can be easily rubbed down to the desired surface.

This applies, of course, to good cabinet work.

Conclusions

Referring to the four factors mentioned at the beginning of this paper, it is possible to state the following conclusions:

1 Lacquer finishes have their limitations.

2 Because of the susceptibility of wood to moisture, particularly during the summer period when it "swells" and during the cold weather when it contracts only "across the grain," its severely unequal contortions have no counterpart in a metal surface which expands and contracts much as does the lacquer film applied to it.

The Technology of Wood Stains and Fillers for Use with Lacquer

Importance of Fundamental Research Work on Development of Sound Undercoating Materials for Use with Lacquer—Progress in Development of Non-Grain-Raising Water Stains and Rapid-Drying Water-Base Fillers

By S. M. SILVERSTEIN,[1] BOSTON, MASS.

THE OBJECT of this paper is to point out the importance of fundamental research work on the development of sound undercoating materials for use with lacquer and to outline the progress already made in one instance on the development of non-grain-raising water stains and rapid-drying water-base fillers.

In a recent issue of the *Scientific American* there appeared the following short editorial:

> The United States Chamber of Commerce says that American manufacturers are spending about $35,000,000 a year on research. This seems like quite a lot of money, especially since most of it sinks out of sight, at least for a while. But the Chamber also estimates that in the long run this same investment saves the manufacturers $500,000,000 a year!
>
> The trouble is, in most cases, that it is a little hard to trace the savings back to the investment, the routes through which they are made being rather indirect. Thus the old-time manufacturer either refused to "throw away" good money on such "nonsense" as hiring high-salaried men to play with a few test tubes of chemicals, or, if he grudgingly spent a little on research he wanted to see results at once. Nowadays, however, only a few hold out against the modern research trend. Research pays tremendous dividends.

Unfortunately the "few who are holding out against the modern research trend" do not represent individual concerns alone, but in several instances entire industries have apparently failed to realize the potential possibilities for increased profits via the scientific route. An outstanding example among the industries that are losing enormous amounts of money which would normally become additional profits are those in the woodworking group.

An analysis of the situation as regards the attitude of industries, such as those included in the woodworking group, toward science and its possibilities indicates that there are two outstanding reasons why they have not made further progress along scientific lines. In the first place, many manufacturers have the general impression that research is profitable only for very large organizations working with synthetic rather than natural products. It must be admitted that the large organizations have capitalized to a very large extent on modern scientific progress, but basically the spirit that prompted this action is probably one of the most important factors in their becoming so powerful. Then, again, there is no doubt that the complex structure of wood, for example, offers many involved problems, but conversely this fact makes a careful study of its properties much more important than if it were a homogeneous, uniform product without any variations in quality. It is safe to say that research pays tremendous dividends to any organization regardless of size. This is particularly true of the woodworking industries, in which field huge fortunes await those who have confidence in science.

Still another reason advanced by those who are neglecting the aid of chemistry and physics is that they have tried to use it but have found that it will not work in their field. In this instance the scientific man must share the burden of blame for this distorted attitude. The manufacturer usually wants to see results at once. The scientific man feeling that his existence depends on immediate results, usually sacrifices thoroughness for speed. Unfortunately this combination rarely succeeds, and at its best merely results in a superficial solution of the problems involved. Knowledge built up on a structure of this sort soon fails to produce results, and science is ejected as having been tried and found wanting.

Thoroughness, on the other hand, does not necessarily require staggering investments in equipment and personnel, but does require good judgment, careful analysis, and time. Furthermore there should also be close coöperation between the laboratory and the plant. One of the outstanding examples of what superficial research leads to is offered by the work that has been done to date on the waterproofing of wood. Many different films have been applied to the surface of wood and their characteristics studied, but obviously protection of this kind is temporary at its best and neglects the condition of the material on which it is applied. Physical changes in the wood originate from within and not on the surface, so that any process involving only a surface treatment merely means "bottling up a tempest."

Similarly when we come to the problem of wood finishing. Once again it is evident that superficial methods of study have retarded progress. It is true, of course, that much of the character of a finish is due to the finish coats; but fully as much, and perhaps more, is dependent on the quality of the foundation on which these finish coats rest. Many instances of defective finishes can be directly traced to improper preparation of the foundation rather than to the surface materials. Yet apparently because the surface finish is what strikes the eye first, almost all research has been confined to this phase of finishing, with the result that there has been no noticeable progress made on lacquer undercoats for wood since the advent of lacquer.

Surface preparation for wood finishing should include attention to the following operations: drying, sanding, sponging, staining, and filling.

The importance of proper drying, sanding, and sponging in the production of a permanent high-grade finish cannot be overemphasized.

Drying determines the condition of the wood, and obviously this plays an important part in determining the effect of time on a given finish. The normal expansion and contraction of a film of finishing material is confined to very narrow limits, and unless the wood is properly dried to a definite moisture content, atmospheric changes will cause serious finishing troubles. A study of finishing conditions should always start with a check-up on the operating characteristics of the dry kilns.

The importance of sanding is more often appreciated than that of drying. This is especially true since the advent of lacquer, with its much lighter body than varnishes. Careful studies have definitely shown that it is much more economical to increase sanding costs in preparing a surface for lacquer than to depend upon subsequent finishing operations to cover defects.

The additional cost of sponging is well justified in the production of high-grade finishes. In its effect it is comparable to the value of sanding with gradual reduction in fineness of paper grit as against a sudden change from coarse to fine paper. It reduces the amount of sanding required after staining, and the net effect is not only to produce a smoother surface but also to reduce the danger of cutting through the stain.

Stains

Types. The three main groups of stains used in wood finishing may be classified as shown in Table 1.

The formulas noted in Table 1 are not intended to represent actual dye compositions, but merely to show the relative differences in the three different types of dyes. Starting with the chromophore or color group there is the neutral coal-tar product representing oil-soluble dyes. The water-stain group is formed by sulfonating the neutral oil dye and thus rendering it soluble

[1] Director, Industrial Research Division, Bigelow, Kent, Willard & Co., Inc.

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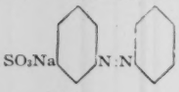
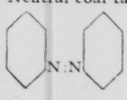
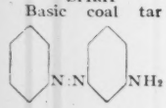
TABLE 1 TYPES OF WOOD STAINS

	Water	Oil	Spirit
Dye	Acid coal tar	Neutral coal tar	Basic coal tar
Formula[a]			
Vehicle	Water	Benzol turpentine	Alcohol
Properties and characteristics	Raises grain Fast to light Uniform Non-bleeding	No grain raising Fades Non-uniform Bleeds	No grain raising Fades badly Non-uniform Bleeds
Method of application	Dip, brush, spray	Dip, brush, spray	Brush
Average cost, cents per gallon	20	100	100

[a] Not actual formulas—used for illustration only.

in water. The group of basic coal-tar dyes is formed by adding an amino group to the color group shown above.

Water Stains. Until the advent of nitrocellulose finishes most of the wood staining was done by using oil or spirit dyes. In the case of high-grade finishes, especially where permanence to light was of importance, water stains were found most satisfactory. The use of lacquers soon showed that oil and spirit stains were unsuited for this class of finishes. Aside from the fading effect of light, lacquer finishing brought up another problem which was even more serious and is best described as bleeding. Bleeding is in reality solution of the dye in the solvents used in compounding lacquer. This effect can be somewhat reduced by the use of shellac or shellac substitutes, but this usually involves sacrificing some of the advantages of a lacquer finish. It has therefore been the accepted practice to recommend the water stains for use with lacquer. Although the disadvantages of water stain have been appreciated, nothing practical has as yet been developed to supplant this type of dye for use with lacquer. From time to time new products have been marketed which were supposed to overcome water-stain disadvantages, but practically all of these products have depended upon sales propaganda rather than merit. A brief study of the action of water on wood will readily convince one that to offset its harmful effects will require intensive research rather than the superficial methods which have apparently existed to date.

When water stain is applied to wood it saturates the fibers both inside and outside, and, on drying, the grain is found to have been raised. This necessitates careful sanding to remove the "whiskers" and at the same time avoid cutting through the stain. If this additional operation ended the problem it would not be so serious, but the wetting of the wood also tends to open its surface structure. This opening action emphasizes the unevenness of the wood surface and so breaks up the reflected light that it is almost impossible to get a so-called "full" finish. With the development of high-solid-content lacquers this effect has been overcome to some extent, but as yet the full bodied effect of varnishes has not been realized.

Oil Stains. On high-grade finishes water stains must be used, but on some of the cheaper lacquer finishes several manufacturers are apparently using oil stains with some success. Aside from bleeding and fading problems which in these instances are apparently not important, there is another problem which must be considered. Oil-stain finishes are subject to peeling; this is in most cases due to the residual oil, which prevents good adhesion of the lacquer film and also tends to ultimately soften the film. This effect can be overcome by careful control of the solvents used. These solvents should be of low volatility and leave no residual wax or grease. Peeling in some cases may also be due to too smooth a prepared surface. In other words, while the grain raising encountered with water stains is undesirable, a certain amount of this action tends to produce a surface into which the finishing films can get a grip and thus adhere more tenaciously. The peeling effect can be reduced to some extent by slightly warming the surfaces to be finished and thus getting somewhat better penetration than at room temperature. At any rate, it is safe to state that most peeling troubles can be overcome by checking up on the boiling point and residue of the solvents used. The amount of bleeding normally encountered when using oil stains has been measured in a dipping process and found to be approximately 6 per cent of the amount of color originally present in the wood. Walnut and mahogany stains do not differ appreciably in this respect.

Spirit Stains. Spirit stains at the present time can be practically neglected as far as use with lacquer is concerned. There is no doubt that a certain development now in progress may soon result in the production of an ideal spirit stain which will not only withstand the action of lacquer solvents but will also be fast to light. As yet, however, certain commercial manufacturing problems and cost considerations relegate this development to that class known as "experimental." Unfortunately this class is altogether too small. Whereas water stains tend to penetrate to the inside of the wood fibers, oil and spirit stains merely color the surface of these fibers. In other words, these two classes of dyes do their coloring between the fibers and thus produce the flecking effect as contrasted to the uniform color of water stains. This is especially noticeable in the case of softwoods and the effect is very undesirable. For this reason we come to the conclusion that the ideal stain for use with lacquer would undoubtedly be a non-grain-raising water stain.

Non-Grain-Raising Water Stain. Research is now in progress on a fundamental study of grain raising and its prevention, and although the results are still incomplete a brief review will be made at this point in an attempt to encourage other investigators who are interested to add their assistance to this work.

It is a well-known fact that benzol does not raise the grain of the wood. Alcohol, on the other hand, raises the grain slightly. Water, however, raises the grain very much. It is obvious that the difference in the action of these three liquids must be due to differences in their chemical or physical properties. Since both physical and chemical properties of a liquid can be modified to a large degree by the addition of other materials to the liquid, studies of this type have been made in an attempt to solve this problem which is of such prime importance to the wood-finishing industry.

The following is the tabulation of the physical properties of the above three liquids:

	Molecular weight	Specific gravity	Surface tension	Viscosity
Water	18	1.0	72.8	1.0
Ethyl alcohol	46	0.8	21.7	0.017
Benzol	78	0.9	29.4	0.009

It would seem as though the specific gravity and viscosity of a liquid would have very little to do with such a phenomenon as grain raising, and in subsequent studies these properties were not considered.

Surface tension was at first thought to be an important factor. But as seen from the above table this property does not fall in line with the grain-raising characteristics of the three liquids.

Molecular weight has a vital relation to the rate of diffusion of a solvent into a solid, and therefore a low-molecular-weight liquid would exert its influence in less time than one of higher molecular weight, but the ultimate results are not affected by this property. This, however, cannot be a controlling factor, inasmuch as benzol does not raise the grain no matter how long the wood is subjected to its action.

Thus it is not believed that the physical properties of the liquid have very much to do with raising of the grain of wood.

This apparently indicates that the action of grain raising is purely chemical, such as solvation or hydration, which results in swelling. The following table shows the results of measurements of the swelling action of water, alcohol, and benzol on oak:

	Water	Alcohol	Benzol
Swelling at end of 1 hr., per cent	2.7	0.7	0.0
Swelling at end of 24 hr., per cent	10.0	6.0	0.0

It will be seen from the above that swelling is in line with the property of grain raising.

Using these data as the starting point, it was felt that the swelling action of water could be reduced to at least the same point as alcohol.

Swelling is a phenomenon which occurs only in colloids and may be compared to the solution of a crystalloid. If common salt (NaCl) is dissolved in water and the solution saturated with hydro-

gen chloride gas (HCl), the salt will be precipitated. Thus it is found that if the water were first saturated with hydrogen chloride gas, salt could not be dissolved by such a solution.

This principle (common ion effect) is applicable to the swelling of colloids. Benzol will swell rubber, but if alcohol is added to a benzol-swollen rubber, it will shrink back to normal size. Thus a mixture of alcohol and benzol will not swell rubber. Water will swell albumen, but if swollen albumen is heated it will shrink and give up water. To prevent the swelling of albumen, there-

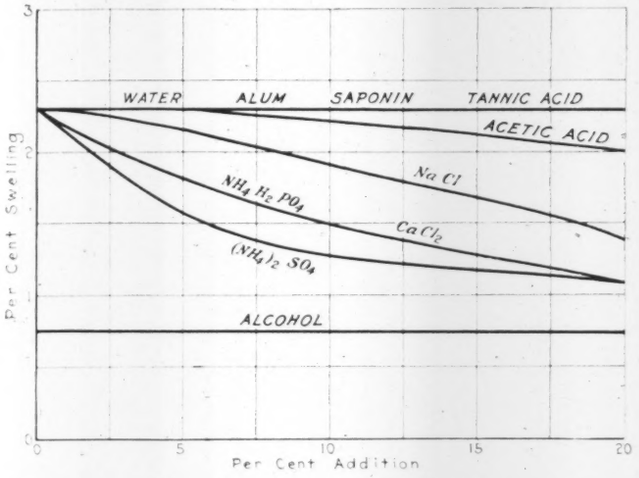


FIG. 1 EFFECT OF VARIOUS SUBSTANCES ADDED TO WATER ON SWELLING OF WOOD, AT END OF ONE HOUR

fore, hot water should be used. Colloidal gold will shrink or coagulate if an electrolyte is added to its water solution. Therefore colloidal gold cannot be prepared in presence of an electrolyte.

Thus, if a coagulating (shrinking) agent or action is added to a swelling agent, swelling can be prevented.

Another method for the prevention of swelling exists in lowering

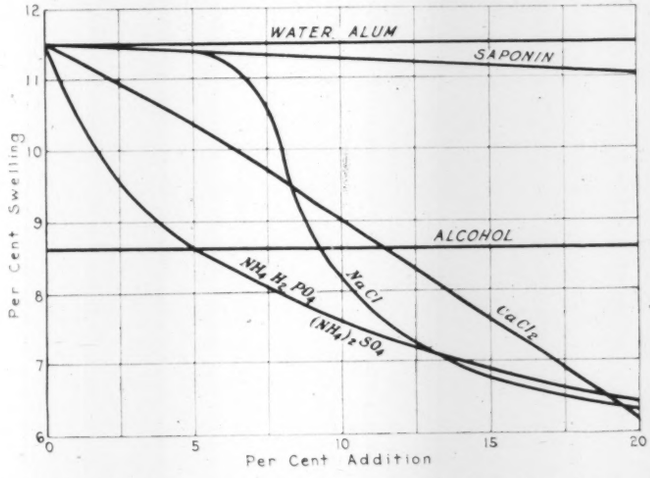


FIG. 2 EFFECT OF VARIOUS SUBSTANCES ADDED TO WATER ON SWELLING OF WOOD AT END OF 72 HOURS

the osmotic pressure of the water by the addition of colloids or electrolytes. This phenomenon may be explained as follows: A substance in solution has a tendency to hold on to the solvent. The solvent in turn has a tendency to be absorbed by wood cells. If the substance dissolved in the solvent is of such nature that it will not diffuse into the cells, two opposing forces are acting on the water. The cells tend to pull the solvent in, and the dissolved substance tends to keep it out. The reduction of the tendency of the water to enter the cells is spoken of as the "lowering of the osmotic pressure."

Still another possibility for prevention of grain raising would be to prepare a water-in-oil emulsion by the use of calcium oleate as an emulsifying agent with a water stain dissolved in the water phase.

The following substances were tried for the purpose of reducing the swelling action of water on wood:

Sodium chloride	5, 10, and 20 per cent solutions
Calcium chloride	5, 10, and 20 per cent solutions
Alum	5, 10, and 20 per cent solutions
Saponin	1, 5 per cent solutions
Ammonium phosphate	5, 10, and 20 per cent solutions
Ammonium sulphate	5, 10, and 20 per cent solutions
Tannic acid	5, 10, and 20 per cent solutions
Acetic acid	5, 10, and 20 per cent solutions
Ten different concentrations of acid	
Alcohol	
Benzol	

The amount of swelling of pieces of oak was determined by means of micrometer measurements to 0.001 in. at one, four, twenty-four, and seventy-two-hour intervals.

Figs. 1 and 2 show the effect of various addition agents on swelling for periods varying from one to seventy-two hours. In addition to the data shown on these curves it has also been found that by the addition of 16 per cent of $AlCl_3$ to certain stains it is possible to reduce the swelling action of water to below that of alcohol. This of course reduces the penetrating powers of the water component, but the latter can be overcome by the addition of certain organic solvents. In this way a solvent is obtained which is suitable for dissolving some of the acid dyes, which thus have the advantages of being fast to light and free from bleeding troubles without raising the grain as much as a spirit stain. At the present

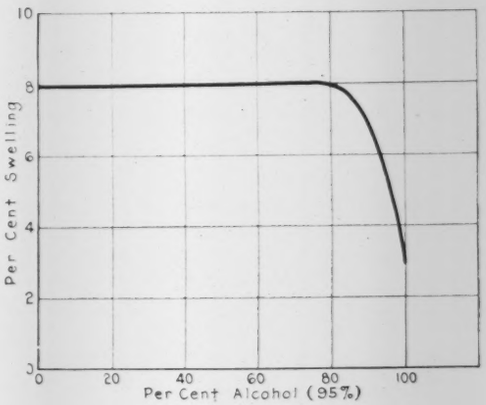


FIG. 3 EFFECT OF ALCOHOL ADDITION ON SWELLING OF WOOD BY WATER

time work is in progress extending the scope of dyes available for this purpose.

From time to time certain wood stains have been marketed which depend on the combination of water and alcohol. Claims have been made that by dissolving an acid dye in water and then diluting it with varying proportions of alcohol, the advantages of each could be obtained without their individual disadvantages. In other words, the presence of alcohol is supposed to reduce the grain raising without affecting the properties of the acid dye. The data plotted in Fig. 3 tend to disprove this contention and show that the addition of alcohol up to 80 per cent of the total volume has practically no effect on the retardation of swelling, which is an index of grain raising. Beyond this point, however, the effect naturally approaches that of pure alcohol.

FILLERS

Oil Fillers. Although some trouble was encountered when lacquers were first applied over the oil fillers normally used for varnish finishes, most of these problems were readily overcome and as far as this type of filler goes there are plenty of satisfactory products on the market. The outstanding difficulty encountered in using oil fillers was that of "graying." In some cases the filling in the pores of the wood changed color immediately, while in other instances "graying" was not noted until months after the finish had been applied. A study of this problem soon showed that this effect was comparable to the "bleeding" of oil and spirit stains under lacquer. In other words, oil-soluble stains were

used for coloring the solid component of the filler, and these stains were of course soluble in the lacquer solvents.

Fillers are in reality highly loaded drying oils. The loading material is usually composed of ground sand, better known as silex. Colors were formerly obtained almost entirely by the addition of aniline dyes, but due to the "graying" action referred to above, coloring effects are now obtained by replacing part of the silex with inert colored pigments. In this way chemical action is avoided, but even in these cases if a filler is of high oil content, lacquer solvents will disintegrate it and float away the pigment. To overcome this action it is therefore advisable to use a short-oil filler with a high mineral content.

Water-Base Fillers. The two highest costs in wood finishing are represented by filling and rubbing. As a matter of fact, filling is the most important of the two inasmuch as it actually affects the rubbing cost. It has been noted that a lacquer finish applied over an oil filler gradually loses its fullness and it is often contended that a permanent lacquer finish cannot be obtained because of the continued shrinkage of the filler and the lacquer film due to the effect of residual lacquer solvents. Of course, after repeated rubbing over periods of several months equilibrium conditions are reached, but obviously this means a large inventory tie-up. Actually what happens is that the lacquer solvents penetrate the filler and make it swell. This condition is temporarily corrected by the rubbing, but with time the filler gradually shrinks back to normal, and then actually contracts. Thus the continuity of the film is impaired necessitating further rubbing.

For this reason the ideal filler should have a binder which is insoluble in lacquer solvents. Due to the powerful action of these solvents it is hard to conceive of any binder that will withstand this solvent action except materials which are water-soluble. Of course at this point the objection may be made that water is slow-drying and also grain-raising in its action. This is true if we consider water actually absorbed in the colloids of the wood. But considering surface drying itself, water is a fairly rapid drying solvent. As a matter of fact, there are only two solvents used in lacquer (ethyl acetate and benzol) which have lower boiling points than water. Yet lacquer is considered a rapid drying material inasmuch as the solvents are not colloidally absorbed but are merely held physically on the surface.

Thus it may be seen that the requisites of a successful filler, using water as the solvent, are a water-soluble colloid such as glue or casein, and another component to keep the water from penetrating the wood. This mixture in dilute form can then be made to act as a binder for the mineral powders which actually do the filling. Casein has some advantages over ordinary animal glue inasmuch as it acts somewhat like a cement, and on hardening frees the water. In this way a "metallizing" effect is approached.

Several fillers of this type have been marketed from time to time, but have had only a limited success because a number of fundamental principles were overlooked. Most of these products have had casein as their base, but have lacked adhesion, hardened too rapidly, and have lacked film flexibility. In short, the problem of fillers of this type should be studied from the same point of view as lacquers themselves; namely,

1 Solvents
2 Film-forming materials
3 Fillers
4 Softeners or plasticizers.

The most promising of all solvents is water.

For film-forming material there is a choice of many components such as casein, glue, starches, and water-soluble gums. In all probability any single one of these substances alone will not solve the problem, but just as in lacquers a combination of two or more may be necessary.

The usual mineral fillers are best suited for filling under these conditions, but the problem of settling out must be considered. Naturally this problem is much more serious with water as the solvent than with the more viscous oils. There is no reason, however, why settling cannot be overcome by the application of protective colloids such as have already been developed for using compounded rubber latex. By this method the individual particles are surrounded with a thin layer of protective colloid material and kept afloat by virtue of the electrical charge they carry. Again, when water is used as the vehicle there is an added possibility of obtaining coloring effects with water-soluble dyes, thus avoiding "bleeding" or "graying."

For softeners or plasticizers there is a wide choice of the more viscous and non-volatile water-soluble oils.

While filling of the wood pores is the prime function of a filler, it should also exert a leveling-off action on the wood and materially reduce subsequent absorption of finishing materials. Much of the "hungry" look encountered when water stains are used should be compensated for by the filler. In other words, a filler should convert the surface of wood to a condition where it approximates the surface of polished metals as regards smoothness and porosity. Literally, the filler should "metallize" the wood surface without affecting the grain appearance. Thus the stain should bring out the beauty of the wood, the filler should bring this beauty to a uniform level and virtually seal it, and the finish coats should permanently protect this beauty against wear.

There is every reason to believe that the work now in progress along the lines discussed above will result in a filler that will combine this metallizing action with a drying time which will more nearly approach that of lacquer instead of the forty-eight hours now required.

Conclusion

Scientific research pays tremendous dividends to any organization regardless of size. This is particularly true of the woodworking industries, where huge fortunes await those who have confidence in science. Successful research requires good judgment, careful analysis, and time. Impatience for immediate results leads to superficial study, which is worthless.

Despite the rapid advance of lacquers, no noticeable progress has been made on lacquer undercoats. Yet many instances of defective finishes can be directly traced to improper surface preparation rather than to the surface materials. Surface preparation includes proper drying, sanding, sponging, staining, and filling. The importance of each of these operations cannot be overemphasized.

The only stains that can be recommended for use with lacquer are those of the acid coal-tar type known as water stains. They are fast to light, do not bleed, but do require additional sanding due to grain raising. For very cheap finishes oil stains can be used, and although they do not raise the grain they fade and bleed. Spirit stains should not be considered for use with lacquer.

Laboratory results indicate that it should be possible to develop a non-grain-raising water stain, and research work along this line is earnestly recommended.

Fillers for use with lacquer should be of short-oil composition and high mineral content. It is very important that the color effect be obtained by replacing part of the silex with inert colored pigments rather than aniline dyes.

A very promising field for intensive research on fillers is that along the lines of using water as a solvent for a water-soluble colloid such as glue or casein and combining this with another component to keep the water from penetrating into the wood. This mixture could then be used as a binder for the regular mineral powders which would do the actual filling. This should produce a filler with a drying time more like that of lacquer.

Statistics show that research returns fifteen dollars for every dollar invested. The woodworker can realize some of these additional profits if he will but consider that research is in the same class as advertising. Constant application cannot fail to produce results.

Determination of the Thermal Conductivities of Insulation for Temperatures up to 1000 Deg. Fahr. on Other Than Flat Surfaces

A Report to the National Research Council Reviewing Past Work, Deducing Defects in Apparatus Hitherto Used and Results Obtained, and Suggesting What Should Be Done to Obtain Accurate and Reliable Apparatus and Test Results

By R. H. HEILMAN,[1] PITTSBURGH, PA.

THE field of heat transmission to be covered in this report is that in non-metallic materials which are used in connection with temperatures from 100 deg. fahr. to 1000 deg. fahr., that is, materials which are classed in the low-temperature-heating field and on up to and including those in the superheated-steam field.

This field of investigation differs from others, first, in that the materials to be tested are to be in a cylindrical form, or are to be powdered materials which can be applied to a cylindrical or spherical form of testing equipment; second, that the materials are liable to be affected by the temperatures to which they are subjected; third, that since the range of temperature is comparatively large, the change of conductivity with temperature—that is, the temperature coefficient—becomes of more importance than with materials used in the refrigerating field; fourth, that since materials are to be tested to 1000 deg. fahr., the design of the testing apparatus so as to obtain a balance in temperature between heating coils and guard-ring coils is of more importance than in the refrigerating field.

The object of this report is (*a*) to review the literature in order to determine what has been done in the past in regard to the practicability and probable accuracy of the apparatus used; and (*b*) to deduce what is lacking in the apparatus used and the values obtained, and to suggest what should be done to obtain accurate and reliable apparatus and test results in a form which can be used to determine the heat transmission for any practical case.

General

The ever-increasing cost of fuel and the tendency toward higher steam pressures and temperatures necessitate the development of better and more suitable heat insulations and also require the dissemination of the results of research obtained by various investigators to the engineering profession at large.

In a field so large as the heat-insulation field there is necessarily a certain amount of investigational work going on at all times. If the work being done by these various investigators could be carried out with such completeness as to allow their results to be applied to any practical case and not solely to the conditions under which the work was carried out, much more valuable information would now be available.

A review of the current literature indicates that a large proportion of the work that has been done in the past has been for the purpose of obtaining overall coefficients only, or when the insulating values of surface films have been added to the insulating values of the insulating materials themselves. The results thus obtained do not lend themselves to the determination of heat losses for other conditions, and do not enable one to determine the true thermal conductivity of the materials tested.

The constant demand for higher efficiencies calls for a more accurate determination of the efficiencies of heat insulation than was required in former days when fuel and labor were cheap. A variation of thermal efficiency of one or two per cent at that time did not carry any great weight either way, but today engineers are beginning to realize that an increase of one-tenth of one per cent in thermal efficiency of a steam-pipe covering when applied to a complete modern power-plant installation results in a tremendous saving when extended over a period of years. The necessity for determining accurately the thermal conductivity of insulating materials is therefore very obvious.

Practical and Theoretical Engineering Requirements

The practical engineer is often interested only in the results of thermal-conductivity tests which are performed under actual operating conditions. He maintains that laboratory tests are unreliable when it comes to applying the results obtained to actual conditions. There is some justification for such an attitude, as it is very hard for the investigator in the laboratory to judge exactly the conditions in the plant, such as steam velocity, velocity and temperature of drafts of air blowing over the insulation, temperature of surfaces to which radiation takes place, etc. Then again there are the vibration of the pipes, steam leaks, mechanical abuse, etc., all of which affect the life of the insulation.

However, these matters should not prevent the greater amount of investigational work on thermal conductivities from being conducted in laboratories, for it is very essential that the various items affecting the transfer of heat be carefully studied and their bearing on the total transfer be determined.

When the effects of all the variables have been accurately determined it will then be possible to calculate the total heat flow for any practical condition, provided, of course, that it will be possible to measure in the plant the extent of the disturbing actions which occur, such as velocity of drafts, etc.

It is very desirable that the major part of the investigational work be conducted in the laboratory, as it is imperative that accurate thermal coefficients be obtained. Highly accurate coefficients cannot be obtained from condensation tests under practical working conditions in the plant. Also the time required to make such tests and the expense they entail are necessarily very great.

In developing and improving heat insulations it is often necessary to conduct a great many tests in the course of a few months. These tests have to be conducted with the utmost care and accuracy in order to check accurately the process of the development and the effect of the many variables that enter into the manufacture of the material. Several testing outfits of identically the same design can be installed in the laboratory and results on a number of samples can be obtained within a few days.

If the apparatus is designed with care, and accurate temperature readings can be obtained so that the investigator can measure the various temperature drops, it should be possible to check the conductivity of any given material with absolute accuracy.

Temperature Gradient from Steam in Insulated Pipe to Surrounding Air

The temperature drop from an insulated steam line to the surrounding air is made up of five distinct items:

(*a*) The drop from the steam to the inner surface of the pipe
(*b*) The drop through the pipe wall
(*c*) The drop from the outer surface of the pipe to the inner surface of the insulation
(*d*) The drop from the inner surface of the insulation to the outer surface of the insulation
(*e*) The drop from the outer surface of the insulation to the surrounding air.

[1] Senior Industrial Fellow, Mellon Institute of Industrial Research.

Contributed by the Committee of Heat Transmission, National Research Council, for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of The American Society of Mechanical Engineers. All papers are subject to revision.

Be sure to bring this copy with you to the Annual Meeting

How these various temperature drops affect the accuracy of thermal conductivity measurements, and the accuracy with which test results can be applied to practical cases, will be discussed briefly.

(*a*) *Temperature Drop from Steam to Inner Surface of Pipe.* Very little investigational work has been done on this item, probably the most extensive being that by Eberle[2] in Munich. Eberle found that for superheated steam the temperature drop varied considerably with the velocity of the steam. A temperature drop of as high as 110 deg. was obtained for an uninsulated pipe with a pressure of 98 lb. and a velocity of 30 ft. per sec. With an insulated pipe the temperature drop was reduced very materially. Too much reliance cannot be placed on the Munich tests, as some of the results obtained were very contradictory and do not agree with results obtained by later investigators studying the emissivity coefficients of bare lines.

Carter and Cope[3] in a paper presented before the A.S.M.E. in 1925 show that the drop from superheated steam to the outside surface of a well-insulated pipe did not exceed 4 deg. for a temperature of approximately 620 deg. In making pipe-covering calculations a drop of 10 deg. is often allowed for superheated steam. The author is of the opinion that this is amply sufficient for most practical cases where efficient insulation is used.

The temperature drop for saturated steam in an insulated pipe is very small and the temperature of the pipe is usually taken as the temperature of the steam in the pipe. It is very desirable that additional investigational work be done along this line so that more definite information may be available. However, the accuracy of thermal-conductivity determinations made on insulations where the temperature of the pipe is measured is unaffected by the drop from the steam to the pipe. The only error involved is that in applying the results obtained to a practical case, and there is no error in the actual determination of the conductivity coefficient of the insulation tested.

(*b*) *Drop Through Pipe Wall.* Owing to the very high thermal conductivity of iron and steel, the temperature drop through the wall of a pipe is very small for any practical case and can in general be entirely neglected, either in calculations or measurements in testing apparatus.

(*c*) *Drop from Outer Surface of Pipe to Inner Surface of Insulation.* This temperature drop depends upon the resistance to heat flow offered by the air space between the surface of the pipe and the inner surface of the insulation, and upon the amount of heat flowing across the air space. Consequently the temperature drop will vary with the kind and thickness of the insulation, the diameter of the pipe, and the thickness of the air space. The nature of the surface of the pipe will also have some effect upon this drop. The author is unaware of any investigational work being done on this item, with the exception of what he has done himself at Mellon Institute.

It is a very difficult matter to measure accurately this temperature drop owing to the difficulty of getting correct temperature measurements of the inner surface of the covering. A great many measurements were taken at Mellon Institute on pipe coverings on various-sized pipes by drilling small holes through the covering and drawing thermocouples through the holes and fastening them to the inner surface of the covering. In making such measurements, however, some of the couples are bound to touch the pipe and will not give true indications; also the pipe covering is rarely absolutely cylindrical and does not fit the pipe snugly at all points, thus creating temperature drops of varying magnitude.

From the results obtained using 6 thermocouples to get an average temperature of inner surface of the covering, it was found that the temperature drop from the pipe to the covering increased as the diameter of the pipe decreased. It is very evident, however, from these tests that it would be almost impossible to predict accurately this temperature drop for any given case, although the drop could probably be estimated to within 10 deg.

This temperature drop is generally neglected when making calculations, the resistance of the film of air being added to the resistance of the insulation. However, when determining the true conductivity of insulating materials it is desirable that this drop be measured as carefully as possible and the conductivity figures based accordingly.

(*d*) *Drop from Inner Surface of Insulation to Outer Surface of Insulation.* The main difficulty in measuring this drop is that of measuring the temperature of the inner surface of the covering as mentioned above. The temperature at the outer surface of the insulation can be measured very accurately by the use of thermocouples placed under paper labels. The method used by the author is as follows: Four thermocouples are placed under paper labels approximately $3^1/_2$ in. long and $1^1/_2$ in. wide, the junction of the couple being at least 3 in. under each label. The couples are placed on each test section and are spaced 90 deg. from each other in a vertical plane at a distance of approximately 16 in. from one end of the section, the couples being placed at an angle of 45 deg. from the horizontal and vertical positions.

Couples placed under the usual canvas jacket of pipe coverings will generally give a temperature approximately 1 deg. fahr. higher than those placed over the canvas. If the conductivity of the canvas covering is not to be included in the calculation, the couples should be inserted under the canvas at least two or three inches to insure correct readings.

The temperature drop through the insulation should be very carefully observed if the results of tests of various types of apparatus are to be compared. It is very probable that the variations in thermal conductivity of similar insulations obtained by various investigators on different types of apparatus are due as much to the failure to obtain correct surface temperatures of the insulation as to the failure to measure accurately the heat flow through the insulations.

Probably the easiest and most accurate method of determining thermal conductivities of insulating materials is by establishing constant heat flow and temperature throughout the insulation. The conductivity can be determined from the temperature at the two surfaces of the insulation, or from the temperature-gradient curve through the insulation and the heat flow through it.

When the conductivity of an insulating material approximates to a linear function of the temperature, the equivalent conductivity for the whole thickness of the insulation is equal to the conductivity corresponding to the arithmetical mean of the two surface temperatures. The conductivity of all types of insulation investigated by the author approximates to a linear function of the temperature. This enables one to determine with sufficient accuracy the conductivity of a material by determining the heat flow through the material and the temperature difference between its two faces. If the mean temperature obtained through a covering is not as high as desired, the conductivity at a much higher mean temperature can be obtained by adding additional insulation to the first insulation and measuring the temperature between the two insulations.

Thermal conductivities determined by the above method will in general be much more accurate than conductivities determined from a temperature-gradient curve and the flow of heat through the covering. While it is true that the relation K = heat flow divided by the temperature-gradient gives the conductivity directly as a function of the temperature of the covering, nevertheless conductivities determined in this manner are seldom accurate, as it is very difficult to obtain true temperature-gradient curves for any insulating material on a cylindrical test pipe.

(*e*) *Drop from Outer Surface of Insulation to Surrounding Air.* This temperature drop when plotted as a function of the heat loss from the outer surface of a pipe covering is very essential in making heat-transfer calculations, when thermal conductivities are to be applied to a practical case where the total heat transfer from pipe to air is wanted.

Considerable work has been done along this line during the past few years by various investigators, but there is still a considerable amount of data lacking.

To be of any practical value, the temperature drop from the outer surface of the insulation to the surrounding air should always be connected with the heat loss from the surface. Some investigators have attempted to separate this heat loss into radiation and convection losses. The loss due to forced convection has also been studied.

The results of such tests are highly important as it is impossible

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[2] *Mitteilungen über Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*, Heft 78.

[3] The Rational Design of Covering for Pipes Carrying Steam up to 800 Deg. Fahr., by W. A. Carter and E. T. Cope. Mechanical Engineering, vol. 47, no. 10, October, 1925, p. 805.

to calculate accurately the heat loss from a given insulated steam line without a knowledge of the emissivity coefficient of the outer surface of the line. This is especially true of flat surfaces, as few data are available on the emissivity from flat surfaces in various positions. Conductivity figures or emissivity figures as a function of the temperature difference between the surface and the ambient temperature should be accurately determined for all types of surfaces met with in engineering practice, such as canvas, weatherproofing, brick, cement, etc., when applied to horizontal and vertical pipes and horizontal and vertical plane surfaces. The coefficients should be obtained for both free and forced convection throughout a considerable temperature range.

The author[4] has made a study of the emissivity coefficient from canvas-covered pipe insulation on horizontal pipes in free air, and has derived the following equations from the results:

$$T_d = \frac{272.5\,h}{h + \frac{564}{D^{0.19}}}$$

$$h = \frac{564\,T_d}{D^{0.19}\,(272.5 - T_d)}$$

where T_d = temperature difference between canvas surface and room, deg. fahr.
h = total B.t.u. loss per hour per square foot of canvas surface
D = outer surface diameter, inches.

No attempt has been made to separate radiation and convection in these experiments, the main purpose being to obtain a combined coefficient which could be readily used by engineers in making pipe-covering calculations. The equations are approximately accurate for diameters of 3 to 24 in. and for room temperatures of 70–90 deg. fahr.

Apparatus for the Determination of the Thermal Conductivity of Pipe Coverings

The apparatus to be described is the type of apparatus now being used at Mellon Institute and is the result of the gradual development of almost 10 years' work on the testing of pipe coverings. This apparatus has been checked in every way possible and the author believes that the accuracy of the apparatus is of a high order.

The general arrangement of apparatus used in testing pipe coverings is shown in Fig. 1. The test pipe is a 3-ft. section of standard 3-in. steel pipe closed at the ends with insulating caps of asbestos lumber and containing three heating coils connected in multiple and wound on a 2-in. enameled steel pipe. The center heating element is wound over a 30-in. length of pipe, while each end heating element is wound over a $2^3/_4$-in. length of pipe. A variable resistance is placed in series with each of these coils to provide a means of regulating the heat supplied to each coil.

While the covering being tested is drying out, the power input to each coil is adjusted until the temperature as indicated by the thermocouples placed in the test pipe is the same over the end coils as that over the central coil. When this condition is reached it is assumed that the power supplied to the central coil is dissipated radially through the covering, thus eliminating any further correction for end losses.

The principal objection that has been raised on this apparatus is the fact that no insulating disks of asbestos boards have been used between the end heaters and the central heaters. In former test pipes used at the Institute insulating disks of asbestos boards were placed between the end heaters and the central heater. However, due to the fact that no heating element could be placed in the space occupied by the asbestos boards, it was found that the temperature at the ends of the central portion of the test pipe was lower than the temperature at the center. This unevenness of temperature probably caused a slight error in the measurement of the true amount of heat passing through the test section. A mechanical difficulty encountered with this arrangement was caused by the central portion of the test pipe not lying in exactly the same horizontal plane as the end sections because of the weakening of the asbestos boards caused by the excessive temperature to which the boards were exposed.

In the present type of construction in which the solid pipe is used no mechanical difficulty is encountered and a very uniform temperature throughout the entire length of pipe is obtained. The author is aware of the fact that, owing to the high thermal conductivity of steel, a small temperature difference will allow considerable heat flow to take place. However, the end caps of the test pipe are always very well insulated with magnesia plastic, and assuming that heat flow took place along the pipe wall from the center heater to the end heater, the excessive amount of heat could not get through the magnesia plastic and would thus raise the temperature at the end of the test pipe, and this higher temperature due to the high conductivity of the steel would in turn transmit the heat back again to the central portion of the test pipe.

This item has also been checked by comparing the heat transmitted per unit of area from the end sections and the central sections to the actual ratio of radiating surface of the central part of the test pipe and the end sections of the test pipe. It has been found that when the insulating caps are thick enough to have approximately the same transmission coefficient as the insulation undergoing test, the power supplied to the end sections is practically

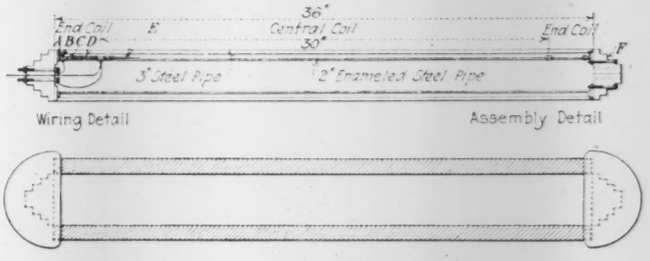

FIG. 1 DEVICE FOR TESTING 3-IN. PIPE COVERINGS
(*A*, 1/8-in. steel end plate; *B*, 1/16-in. steel spacing ring; *C*, Transite bushing; *D*, No. 26 B. S. No. 193 alloy wire, 22 turns per inch; *E*, No. 14 B. S. No. 193 alloy wire, 6 turns per inch; *F*, Transite end.)

the same per unit area as the power supplied to the central section per unit area.

When the thickness of the insulation of the end caps is insufficient, it has been found that more heat has to be supplied to the end section per unit area. When the caps are thicker than required the reverse has been found to be true. This means that the amount of heat applied to the end sections automatically corrects for the end loss, so that very little error is involved when the ends and central portion of the heater are properly balanced.

Additional Apparatus Required for the Determination of the Thermal Conductivity of Pipe Coverings

The additional apparatus required for the accurate testing of pipe coverings is as follows: potentiometer, wattmeter, rheostats, transformer, thermocouples, dial test indicator, and thermometers.

Potentiometer. This instrument is used in determining the temperature of the pipe and the outer surface temperature of the pipe covering. The Leeds & Northrup Type K potentiometer is an excellent instrument for this type of work. If not available, a portable potentiometer manufactured by the Leeds & Northrup Company or its equivalent, having a range of 0–16 millivolts and 0–80 millivolts, should be substituted.

Wattmeter. This instrument is used in measuring the power supplied to the heating coils of the pipe covering tester. The Weston Model 310 wattmeter having a range of 250, 500, and 1000 watts or its equivalent should be supplied.

Rheostats. Three rheostats are required for the purpose of varying the power input to the center heating coil and the two end coils of the pipe-covering tester. Two rheostats having a current-carrying capacity of approximately 2.5 amperes and a resistance of approximately 45 ohms, and one rheostat having a current-carrying capacity of approximately 10 amperes and a resistance of approximately 5 ohms, should be supplied.

Transformer or Variable Resistance. It is necessary to have some means of varying the total power input to the pipe-covering tester so that the temperature range of the tester can be varied from, say, 100 deg. fahr. to 1000 deg. fahr. If alternating current is available, as is usually the case, a small auto transformer of approximately

[4] MECHANICAL ENGINEERING, vol. 46 (1924) no. 10 p. 593.

1 kw. capacity and having a voltage range of from 2 to 110 volts in 2-volt steps is desirable.

A brief description of such a transformer to operate on a 110-volt single-phase line is as follows:

The core consists of silicon-steel transformer iron having a cross-sectional area of 1.5 sq. in. assembled as a core-type transformer, the outside dimensions of the assembled core being 5.4 in. by 7.6 in. One leg of the core is wound with 100 turns of No. 8 D.C.C. (double

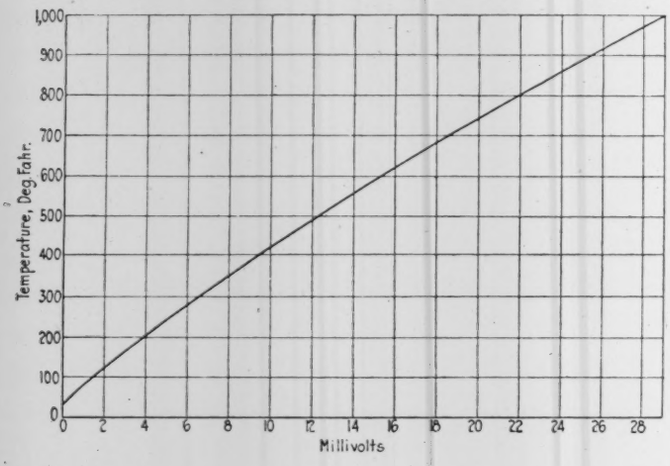

FIG. 2 CALIBRATION CURVE FOR COPPER-CONSTANTAN THERMOCOUPLES

cotton covered) magnet wire, the first 25 turns being tapped every 5 turns and the last 75 turns every 25 turns.

The second leg is wound with 175 turns of No. 11 D.C.C. magnet wire tapped every 25 turns. The two coils are then connected in series so as to make a continuous winding of 275 turns. This arrangement will give 10 taps supplying 10 volts between each tap and 5 taps supplying 2 volts between each tap, so that any even voltage from 2 to 110 can be obtained from this transformer by the proper selection of voltage taps.

Thermocouples. A spool of D.C.C. copper wire and one of D.C.C. constantan wire, No. 25 to No. 29 gage, should be supplied for thermocouples. The thermocouples should be made by electrically welding the two dissimilar wires together so as to form a small bead at the junction or by twisting the two ends together and silver-soldering. A calibration curve for copper-constantan thermocouples is shown in Fig. 2.

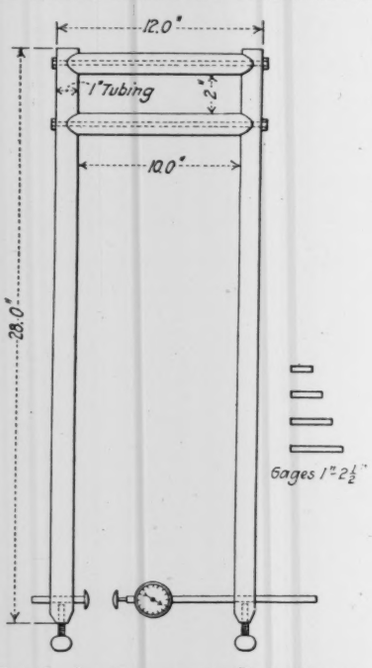

FIG. 3 INSTRUMENT FOR DETERMINING THICKNESS OF MATERIAL TO BE TESTED

Dial Test Indicator. This instrument is used to determine the thickness of the insulation to be tested. It consists of a dial graduated to read to 0.001 in. which is adjustable to allow the setting of the zero to any required position. The spindle should have at least 0.25 in. movement. The assembly of this instrument in a suitable frame is shown in Fig. 3.

Mercury Thermometers. Two good-grade mercury thermometers having a range of 110 deg. fahr. should be provided for room-temperature determinations.

Apparatus Assembly. A wiring diagram of the apparatus is shown in Fig. 4. The input to the transformer should have a voltage variation not greater than ± 0.25 per cent. This is necessary in order to obtain accurate and consistent results.

PREPARATION OF TEST SAMPLES

The test samples should be carefully examined for cracks, broken pieces, mashed ends, excessive moisture, etc. The insulation should be weighed both before and after the test, and if the sample is of the laminated type the number of layers of paper per inch should be noted and recorded. The length of the sample should be determined to $^1/_{16}$ in., and the thickness to 0.01 in. with the dial test indicator. Thirty thickness readings should be taken with the dial test indicator on each 3-ft. section as shown in Fig. 5. The average of the 30 readings to be taken as the thickness of the sample.

Great care should be exercised in determining the mean thickness of the insulation to be tested, as an error of 0.01 in. in thickness on a standard-thickness covering is of considerable importance, especially if one is checking one covering against another in the process of development work.

APPLICATION OF TEST SAMPLE

Before applying the test sample to the test pipe, 10 copper-constantan thermocouples should be inserted in the pipe as shown in Fig. 6 by drilling a hole slightly greater in diameter than the diameter of the bead of the junction and about $^1/_{16}$ in. deep. The junction is placed in this hole and fastened securely by peening the metal of the pipe against the thermocouple junction by means of a hammer and center punch.

Great care should be taken to see that the junction of the thermocouple does not extend above the level of the pipe or that the thermocouple wires do not touch each other at any point above the junction. The thermocouples should all be rewelded and reset at least every third test.

The covering should be placed on the test pipe with the horizontal

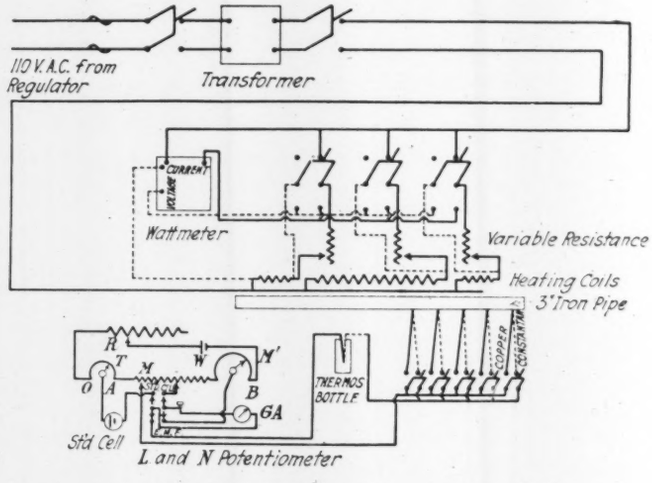

FIG. 4 WIRING DIAGRAM OF APPARATUS SHOWN IN FIG. 1

joint at the top of the pipe, so that when closed in tight the two walls of the covering fit up against the thermocouple wires. The hinge of the covering will then be at the bottom of the pipe.

The fit of the covering on the pipe should be noted and recorded. If the covering fits so tight on the pipe that the walls of the covering do not come together at the top, the resulting crack should be filled with 85 per cent magnesia plastic cement. The canvas flap of the covering should then be pasted down and three bands applied, one at each end and one at the center of the section.

The thermocouples for the determination of the canvas temperature should be placed under paper labels applied to the outer surface of the canvas jacket, the junction of the couple being at least 3 in. under the label. Four couples should be placed on the test section and the couples should be spaced 90 deg. from each other in a vertical plane at a distance of approximately 16 in. from one end of the section, the couples being placed at an angle of 45 deg. from the horizontal and vertical positions.

The crack between the ends of the covering and the end caps should then be sealed with 85 per cent magnesia cement. The end caps should be made of 85 per cent magnesia cement, and after they have become hard it will be unnecessary to remove them from

the test pipe as they will serve for a great many tests before replacement is necessary.

METHOD OF PROCEDURE IN TESTING

The temperature of the test pipe should be raised to the highest temperature that the covering is to be tested at and allowed to remain at that temperature for from 24 to 48 hours to insure thorough drying out of the test sample.

There is some question as to the advisability of immediately raising the temperature of the test pipe to the highest temperature that the covering is to be tested at, owing to the change in thermal conductivity in the covering brought about by the effects of the heat. If the pipe is raised to, say, 300 deg. and readings taken from this point on up to, say, 700 deg., depending upon the character of the insulation, and readings are then taken on a descending-temperature run, it will in general be found that two conductivity curves differing from each other will result, depending again on the nature of the covering. However, the temperature at which the covering should be used should be the criterion as to whether ascending and descending curves are to be employed. In general, it will be preferable to run the descending curve only.

Readings of power input to the center heater and temperature readings of all the thermocouples and the thermometers should be taken. During the drying-out period temperature readings of the test pipe should be taken, and if the temperature over the end coils is higher or lower than the temperatures over the central coil the resistance of the rheostats should be changed until the temperature readings over the end coils is the same as over the central coil.

When the temperature is balanced once for each test it will be found that it is seldom necessary to rebalance the coils for the remainder of the test. It is advisable to take a preliminary reading in the morning to allow for adjustments if necessary, and then readings every half-hour during the afternoon until the readings become constant.

One reading should be taken each day at approximately 100 deg. fahr. lower than the reading of the previous day until at least 5 readings in all have been taken. The results of the readings calculated to B.t.u. per hour per degree fahrenheit temperature difference should be plotted each day on cross-section paper. The plots deviate very slightly from a straight line drawn through them, as it will generally be found that if the test is conducted carefully the plots will not vary more than 0.5 per cent from a straight-line relation.

During the test period it is imperative that the wattmeter switch for the central coil should be in the down position at all times, both night and day. This is especially imperative if the current coil of the wattmeter used has any appreciable resistance.

In checking the conductivity of insulating materials from various manufacturers it is very desirable that as many tests as possible be conducted on each material from each manufacturer as the results of only one test on each material are apt to be misleading, owing to the variation between individual samples made by the same manufacturer.

A sample data sheet of the readings taken on a pipe covering during a test run are shown in Table 1. A check test on the same covering but on another test pipe is shown in Table 2. The results of these two tests in terms of the overall conductivity of the covering are shown in Fig. 7. A careful examination of the two curves shows how very closely the two pipe-covering testers check each other.

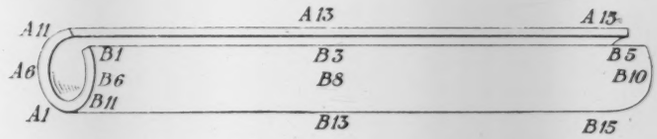

FIG. 5 LOCATION OF THICKNESS MEASUREMENTS

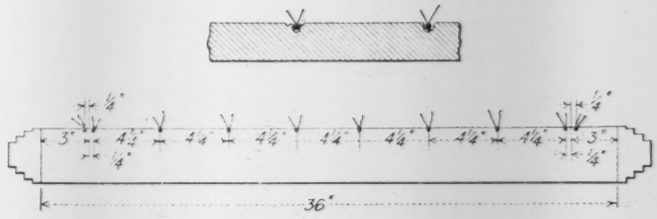

FIG. 6 LOCATION OF THERMOCOUPLES

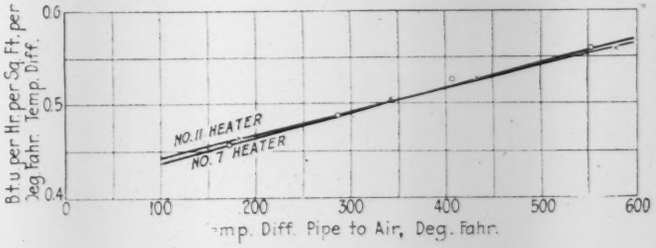

FIG. 7 OVERALL CONDUCTIVITY OF COVERING 0.98 IN. THICK ON 3-IN. PIPE

TABLE 1 SAMPLE DATA SHEET TAKEN ON A PIPE COVERING DURING A TEST RUN

Test No. 564. Heater No. 11. Heater Const. 1.49. Pipe Diam. 3 in. Covering, 0.97 in. thick. Nature of Test .....

Mo.	Day	Hour a.m. or p.m.	Watts 1	Watts C	Watts 2	Room temp. 1	2	3	4	Avg.	Thermocouples (see chart under Remarks) 1	2	3	4	5	6	7	8	9	10	Avg.	Calculations and Remarks
4	1	4:00	37.5	207	38.					74.0	16.28	16.30	16.29	16.29	16.25	16.29	16.28	16.27	16.21	16.23	16.27	=626°
											2.95	2.95	2.88	2.98		Surface		Avg.	=	2.94	=162°	
																						$K_0 = \frac{1.49 \times 207}{552} = 0.558$
4	3	4:00	24.7	143.2	26.0					78.0	11.86	11.88	11.88	11.89	11.87	11.91	11.92	11.91	11.87	11.89	11.89	=485°
											2.40	2.51	2.32	2.55				Avg.	=	2.44	=143°	
																						$K_0 = \frac{1.49 \times 143.2}{407} = 0.525$
4	4	4:00	16.5	93.5	17.0					75.0	8.24	8.27	8.25	8.25	8.23	8.26	8.27	8.27	8.25	8.25	8.25	=361°
											1.96	1.96	1.85	2.00				Avg.	=	1.94	=120°	
																						$K_0 = \frac{1.49 \times 93.5}{286} = 0.487$
4	5	3:00	9.0	53.0	9.5					76.5	5.17	5.18	5.18	5.19	5.19	5.21	5.22	5.22	5.22	5.23	5.20	=250°
											1.56	1.63	1.49	1.65				Avg.	=	1.58	=104°	
																						$K_0 = \frac{1.49 \times 53}{173.5} = 0.454$

TABLE 2 CHECK TEST ON COVERING OF TABLE 1, BUT ON ANOTHER TEST PIPE

Test No. 564. Heater No. 7. Heater Const. 1.49. Pipe Diam., 3 in. Covering, 0.97 in. thick. Nature of Test .....

Mo.	Day	Hour a.m. or p.m.	Watts 1	Watts C	Watts 2	Room temp. 1	2	3	4	Avg.	Thermocouples (see chart under Remarks) 1	2	3	4	5	6	7	8	9	10	Avg.	Calculations and Remarks
3	16	4:00		212.5						78.0	16.84	16.87	16.96	16.80	16.78	16.85	16.78	16.83	16.81	16.77	16.86	=645
																						$K_0 = \frac{1.49 \times 212.5}{567} = 0.559$
3	17	4:00		153						77.5	12.64	12.65	12.73	12.63	12.61	12.66	12.61	12.63	12.60	12.56	12.64	=510
																						$K_0 = \frac{1.49 \times 153}{432.5} = 0.527$
3	18	4:00		115						77.6	9.86	9.89	9.96	9.89	9.86	9.90	9.84	9.85	9.80	9.77	9.87	=416
																						$K_0 = \frac{1.49 \times 115}{341} = 0.507$
3	19	4:00		57.5						76.0	5.43	5.47	5.49	5.46	5.44	5.47	5.44	5.44	5.40	5.39	5.45	=260
																						$K_0 = \frac{1.49 \times 57.5}{184} = 0.466$

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Calculation of Results

While the ideal way of representing the results of thermal-conductivity measurements is in the form of absolute-conductivity curves, where the absolute conductivity in B.t.u. per hour per square foot per degree fahrenheit temperature difference is plotted as a function of the mean temperature difference between the inner and outer surfaces of the covering, many engineers are also interested in the overall conductivity or the conductivity values in overall terms as a function of the temperature difference between the pipe surface and the surrounding air.

The overall conductivity or the conductivity of the pipe covering plus the insulating value of the air film around the outer surface of the covering and the outer surface of the pipe is not a true value of the covering itself and will vary with the same insulation as the thickness of the covering and the size of the pipe upon which the covering is tested, etc., are varied.

The absolute conductivity of a covering in B.t.u. per hour per square feet per inch thickness per degree fahrenheit temperature difference when plotted as a function of the mean temperature between the inner and outer surfaces of the covering is a specific property of the material composing the covering and is the same

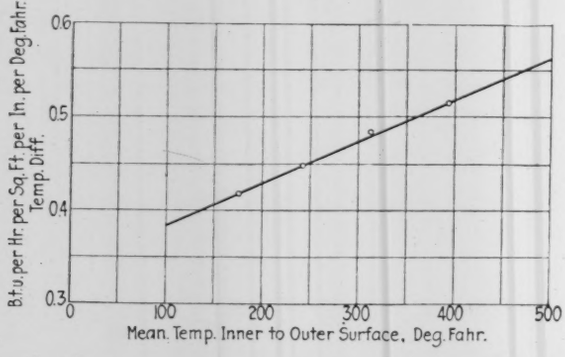

Fig. 8 Absolute Conductivity of Covering 0.98 In. Thick on 3-In. Pipe

for any given material regardless of the thickness of the covering, size of the pipe upon which it is tested, etc.

The method used in calculating and plotting the overall and absolute conductivities from the test data shown in Fig. 7 will be illustrated by examples.

Overall Conductivity. Since the conductivity is generally expressed in B.t.u. per hour per square foot per degree fahrenheit temperature difference, it will be necessary to determine the number of B.t.u. passing through the covering per square foot of pipe surface or inner surface of the covering.

From the data shown in Fig. 1 it will be seen that the effective area of the center heater is over the 30-in. length of 3-in. pipe. Since the power supplied to the central heater is measured in watts (W) and since one watt-hour = 3.415 B.t.u., the number of B.t.u. passing through each square foot of covering = $W \times 3.415 \times 144/(2\pi \times 1.75 \times 30) = 1.49\,W$, or = 1.49 × watts indicated on the wattmeter when the center switch only is in the down position, the two end switches being in the upper position.

The value 1.49 is the constant for the heater and will always be the same regardless of the thickness of the test piece.

The overall loss through the covering for the first reading is then = 1.49 × 207 = 308 B.t.u. per sq. ft. of pipe surface. The overall conductivity per degree fahrenheit temperature difference = 1.49 × 207/(626 — 74) = 308/552 = 0.558.

The data for the other three readings are calculated in the same manner and the results are plotted in Fig. 7.

Absolute Conductivity. The absolute conductivity is calculated from the formula

$$K = \frac{Hr_1 \log_e \frac{r_2}{r_1}}{t_1 - t_2}$$

in which

H = total heat loss per square foot of pipe surface
r_1 = radius of inner surface of covering
r_2 = radius of outer surface of covering
t_1 = temperature of inner surface of covering
t_2 = temperature of outer surface of covering.

Owing to the difficulty of obtaining accurate readings of the inner surface of the covering these readings are not included in the data shown in Tables 1 and 2. The conductivity is figured on the assumption that the inner surface of the covering is at the same temperature as the pipe, also that the radius of the inner surface of the covering is the radius of the outer surface of the pipe.

The absolute conductivity of the covering corresponding to the first reading is then $= \frac{308 \times 1.75 \log_e (2.72/1.75)}{626 - 162}$; the value of 1.75 log. (2.72/1.75) is taken from Table 3 for a covering 0.97 in. thick and is found to = 0.771. $\therefore K = 308 \times 0.771/464 = 0.513$. The mean temperature corresponding to this reading = (626 + 162)/2 = 394 deg.

The data for the other three readings are calculated in the same manner and the results are plotted in Fig. 8.

The absolute-conductivity curve shown in Fig. 8 is the type of curve which should be used in comparing the insulating value of all insulations tested, as the conductivity curve is probably the most important item of the test results.

After completion of the conductivity test the covering should be removed from the test pipe, weighed, and carefully examined for

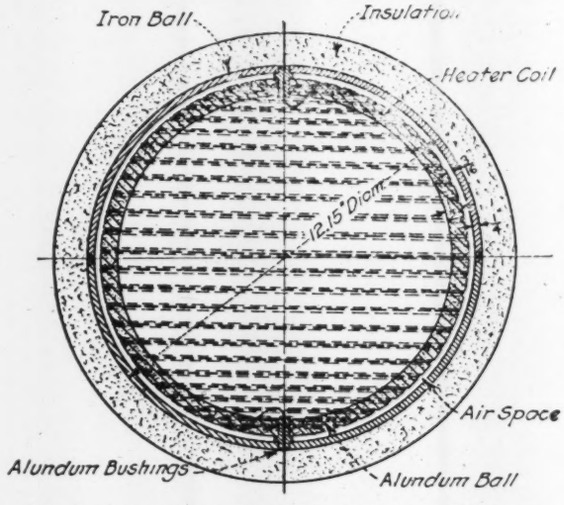

Fig. 9 Apparatus for Testing Insulating Cements

the effects of the heat encountered during the test. Calcination, softening or powdering, weakening of asbestos paper, separation of layers, sagging of covering, etc., should be noted and recorded.

Description of Apparatus Used in Testing Heat-Insulating Cements

The apparatus shown in Fig. 9 which is used in testing heat-insulating cements consists of a cast-iron ball 12.05 in. in diameter and $^1/_4$ in. thick, inside of which is centered an alundum ball $^1/_2$ in. thick whose outer surface at all points is $^3/_{16}$ in. from the inner surface of the iron ball. The alundum ball is grooved for a heating coil of resistance wire which is spaced so as to give a uniform distribution of heat over the entire surface of the ball. Since the surface of the iron ball is that of a uniform sphere, it is unnecessary to have any guard-ring coils to take care of end losses as is required in the cylindrical testing apparatus.

The temperature of the outer surface of the iron ball or the temperature of the insulating cement applied to the surface of the ball is measured by 6 thermocouples uniformly spaced around the circumference of the ball in a vertical plane. These thermocouples are peened into the surface of the iron in the same manner as those in the cylindrical test pipes.

The cement to be tested is applied to the surface of the iron ball with a trowel and the uniformity of the thickness of cement applied is determined by means of templets. The actual thickness of the cement applied is determined by ten measurements of the circumference over the cement.

TABLE 3 VALUES OF $1.75 \log_e \frac{r_2}{1.75}$

Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$	Value of x in $r_2 = r_1 + x$	$r_1 \log_e r_2/r_1$
0.65	0.554	1.03	0.808	1.41	1.035	1.79	1.233	2.17	1.409	2.55	1.570	2.93	1.719	3.31	1.856
0.66	0.561	1.04	0.813	1.42	1.040	1.80	1.237	2.18	1.413	2.56	1.575	2.94	1.723	3.32	1.860
0.67	0.568	1.05	0.820	1.43	1.045	1.81	1.242	2.19	1.417	2.57	1.579	2.95	1.726	3.33	1.864
0.68	0.575	1.06	0.827	1.44	1.050	1.82	1.246	2.20	1.422	2.58	1.584	2.96	1.730	3.34	1.867
0.69	0.583	1.07	0.833	1.45	1.056	1.83	1.250	2.21	1.427	2.59	1.588	2.97	1.734	3.35	1.870
0.70	0.590	1.08	0.840	1.46	1.060	1.84	1.256	2.22	1.433	2.60	1.591	2.98	1.737	3.36	1.873
0.71	0.596	1.09	0.846	1.47	1.066	1.85	1.261	2.23	1.437	2.61	1.595	2.99	1.741	3.37	1.877
0.72	0.604	1.10	0.581	1.48	1.071	1.86	1.266	2.24	1.441	2.62	1.600	3.00	1.745	3.38	1.880
0.73	0.611	1.11	0.858	1.49	1.076	1.87	1.270	2.25	1.445	2.63	1.604	3.01	1.749	3.39	1.884
0.74	0.616	1.12	0.865	1.50	1.082	1.88	1.275	2.26	1.449	2.64	1.607	3.02	1.752	3.40	1.888
0.75	0.624	1.13	0.871	1.51	1.087	1.89	1.279	2.27	1.453	2.65	1.611	3.03	1.756	3.41	1.892
0.76	0.630	1.14	0.876	1.52	1.093	1.90	1.284	2.28	1.457	2.66	1.615	3.04	1.760	3.42	1.895
0.77	0.638	1.15	0.882	1.53	1.097	1.91	1.288	2.29	1.461	2.67	1.618	3.05	1.764	3.43	1.898
0.78	0.644	1.16	0.888	1.54	1.103	1.92	1.294	2.30	1.465	2.68	1.622	3.06	1.767	3.44	1.901
0.79	0.651	1.17	0.895	1.55	1.109	1.93	1.298	2.31	1.471	2.69	1.626	3.07	1.770	3.45	1.904
0.80	0.658	1.18	0.900	1.56	1.113	1.94	1.303	2.32	1.476	2.70	1.630	3.08	1.774	3.46	1.907
0.81	0.664	1.19	0.905	1.57	1.119	1.95	1.308	2.33	1.482	2.71	1.635	3.09	1.779	3.47	1.910
0.82	0.671	1.20	0.912	1.58	1.123	1.96	1.313	2.34	1.486	2.72	1.640	3.10	1.783	3.48	1.914
0.83	0.679	1.21	0.918	1.59	1.130	1.97	1.318	2.35	1.490	2.73	1.644	3.11	1.786	3.49	1.917
0.84	0.685	1.22	0.923	1.60	1.135	1.98	1.322	2.36	1.496	2.74	1.648	3.12	1.789	3.50	1.920
0.85	0.693	1.23	0.930	1.61	1.141	1.99	1.327	2.37	1.500	2.75	1.652	3.13	1.792	3.51	1.923
0.86	0.699	1.24	0.936	1.62	1.145	2.00	1.332	2.38	1.504	2.76	1.655	3.14	1.796	3.52	1.926
0.87	0.706	1.25	0.942	1.63	1.149	2.01	1.336	2.39	1.507	2.77	1.659	3.15	1.799	3.53	1.930
0.88	0.713	1.26	0.948	1.64	1.155	2.02	1.341	2.40	1.510	2.78	1.662	3.16	1.803	3.54	1.933
0.89	0.719	1.27	0.954	1.65	1.160	2.03	1.347	2.41	1.514	2.79	1.666	3.17	1.807	3.55	1.936
0.90	0.726	1.28	0.961	1.66	1.165	2.04	1.352	2.42	1.518	2.80	1.670	3.18	1.811	3.56	1.940
0.91	0.733	1.29	0.966	1.67	1.171	2.05	1.356	2.43	1.523	2.81	1.674	3.19	1.814	3.57	1.944
0.92	0.739	1.30	0.972	1.68	1.175	2.06	1.361	2.44	1.527	2.82	1.678	3.20	1.817	3.58	1.947
0.93	0.745	1.31	0.978	1.69	1.180	2.07	1.365	2.45	1.531	2.83	1.682	3.21	1.820	3.59	1.950
0.94	0.752	1.32	0.983	1.70	1.186	2.08	1.369	2.46	1.534	2.84	1.686	3.22	1.824	3.60	1.953
0.95	0.759	1.33	0.989	1.71	1.192	2.09	1.374	2.47	1.537	2.85	1.690	3.23	1.828	3.61	1.956
0.96	0.765	1.34	0.994	1.72	1.197	2.10	1.379	2.48	1.541	2.86	1.694	3.24	1.831	3.62	1.960
0.97	0.771	1.35	1.000	1.73	1.202	2.11	1.383	2.49	1.546	2.87	1.697	3.25	1.835	3.63	1.964
0.98	0.778	1.36	1.006	1.74	1.207	2.12	1.387	2.50	1.550	2.88	1.702	3.26	1.839	3.64	1.967
0.99	0.783	1.37	1.012	1.75	1.211	2.13	1.392	2.51	1.555	2.89	1.705	3.27	1.842	3.65	1.970
1.00	0.789	1.38	1.017	1.76	1.217	2.14	1.396	2.52	1.559	2.90	1.708	3.28	1.846	3.66	1.973
1.01	0.795	1.39	1.023	1.77	1.221	2.15	1.400	2.53	1.564	2.91	1.711	3.29	1.850	3.67	1.976
1.02	0.801	1.40	1.028	1.78	1.227	2.16	1.405	2.54	1.567	2.92	1.715	3.30	1.853	3.68	1.979

The temperature of the outer surface of the cement is measured with four thermocouples uniformly spaced around the circumference, the thermocouples being held to the surface of the cement by gummed labels $1^{9}/_{16}$ in. by $3^{13}/_{16}$ in. in size.

The most important points to be noted when testing insulating cements are insulating value, covering capacity, sticking qualities, shrinkage, and cracking.

The insulating value is obtained from the heat loss through the cement, the temperature at the two surfaces, and the room temperature. The covering capacity is obtained approximately by weighing the amount of cement removed from the apparatus after the test is finished. The sticking qualities, shrinkage, and cracking can be determined from personal observation.

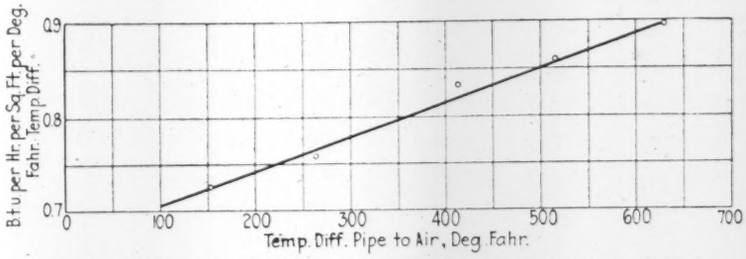

FIG. 10 OVERALL CONDUCTIVITY, CEMENT 1.21 IN. THICK ON 12-IN. SPHERE

A sample data sheet of the readings taken during a test run is shown in Table 4. The method used in calculating and plotting the overall and absolute conductivities from the test data in Table 4 will be illustrated by examples.

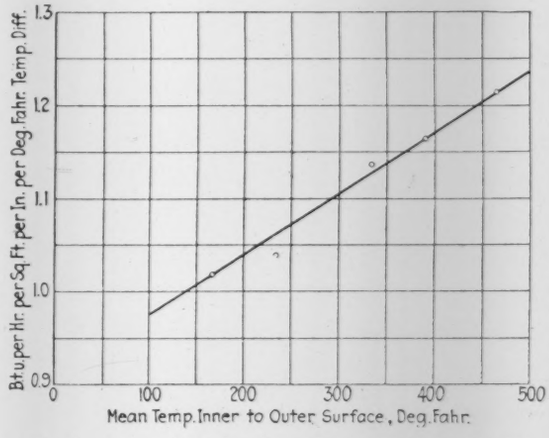

FIG. 11 ABSOLUTE CONDUCTIVITY, CEMENT 1.21 IN. THICK ON 12-IN. SPHERE

Overall Conductivity. From the dimensions given in Fig. 9 it will be noted that the outer diameter of the cast-iron ball is 12.05 in. The surface area is therefore $12.05^2 \times \pi = 465$ sq. in. Since

TABLE 4 SAMPLE DATA SHEET OF READINGS TAKEN DURING A TEST RUN

Test No. 556. Heater No. Ba 11. Heater Const. 1.08. Pipe Diam. ....in. Covering 1.21 in. thick. Nature of Test .....

Mo.	Day	Hour a.m. or p.m.	Watts 1	Watts C	Watts 2	Room temp. 1	2	3	4	Avg.	Thermocouples (see chart under Remarks) 1	2	3	4	5	6	7	8	9	10	Avg.	Calculations and Remarks
1	11	4:00		521						69.5	20.08	19.82	19.49	20.12	19.71	19.41					Avg. 19.77	= 698
											4.95	4.11	4.64	4.90	Surface						Avg. 4.65	= 230
																						$K_0 = \frac{1.08 \times 521}{628.5} = 0.895$
1	12	4:00	410							66	16.60	16.29	16.03	16.62	16.21	15.99					Avg. 16.29	= 582
											4.09	3.46	3.67	4.12							Avg. 3.84	= 198
																						$K_0 = \frac{1.08 \times 410}{516} = 0.859$
1	13	4:00		318						70.5	13.59	13.30	13.09	13.58	13.20	13.04					Avg. 13.30	= 484
											3.51	2.98	3.36	3.63							Avg. 3.37	= 179
																						$K_0 = \frac{1.08 \times 318}{413.5} = 0.832$
1	14	4:00		184						68	8.89	8.66	8.53	8.87	8.57	8.50					Avg. 8.67	= 331
											2.47	2.13	2.37	2.52							Avg. 2.37	= 138
																						$K_0 = \frac{1.08 \times 184}{262.8} = 0.756$
1	15	4:00		102						70	5.61	5.45	5.38	5.58	5.34	5.37					Avg. 5.455	= 222
											1.83	1.62	1.75	1.89							Avg. 1.77	= 113
																						$K_0 = \frac{1.08 \times 102}{152} = 0.725$

one watt-hour = 3.415 B.t.u., the number of B.t.u. passing through each square foot of surface of inner surface of insulating cement = $W \times 3.415 \times 144/456 = 1.08\ W$.

The overall loss through the insulating cement for the first reading is then = $1.08 \times 521 = 563$ B.t.u. per sq. ft. of inner surface. The overall conductivity per degree fahrenheit temperature difference = $1.08 \times 521/(698 - 69.5) = 0.895$.

The data for the other four readings are calculated in the same manner and the results are plotted in Fig. 10.

Absolute Conductivity. The absolute conductivity through a spherical shell is calculated from the formula

$$K = \frac{H(r_2 - r_1)r_1}{(t_1 - t_2)r_2}$$

in which the values are the same as for the pipe-covering tester. The absolute conductivity of the cement corresponding to the first reading is then

$$H\,\frac{(7.235 - 6.025) \times 6.025}{(t_1 - t_2) \times 7.235} = \frac{1.007\ H}{t_1 - t_2} = \frac{1.007 \times 563}{698 - 280}$$

$$= 1.213 \text{ B.t.u.}$$

The mean temperature corresponding to this reading = $(698 + 230)/2 = 464$. The data for the other four readings are calculated in the same manner and the results are plotted in Fig. 11.

Absolute-conductivity values obtained from this type of apparatus should give accurate results as there are no end losses to take care of and there is no surface resistance between the iron surface and the cement. The accuracy will therefore depend mainly upon the accuracy with which the surface temperatures and especially the outer temperature is measured.

This apparatus can also be used for the testing of powdered material which cannot be made into the form of a cement. To take care of powdered material it is necessary to place a thin iron or copper sphere in two pieces around the iron ball and at a distance of about 1 in. from the ball. The upper hemisphere is provided with a small opening at the top through which the powdered material is poured, until the space between the walls is entirely filled. The opening at the top is then closed and the test is started.

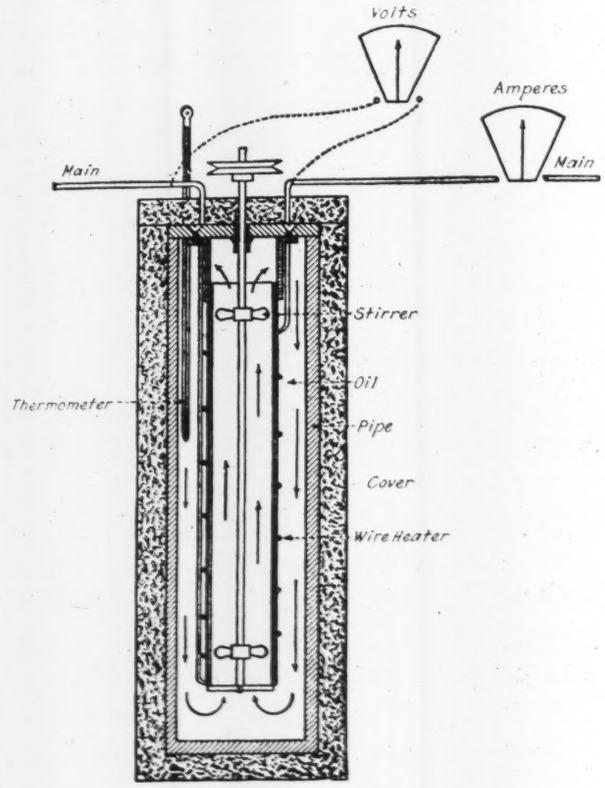

Fig. 13 Apparatus Used by Norton

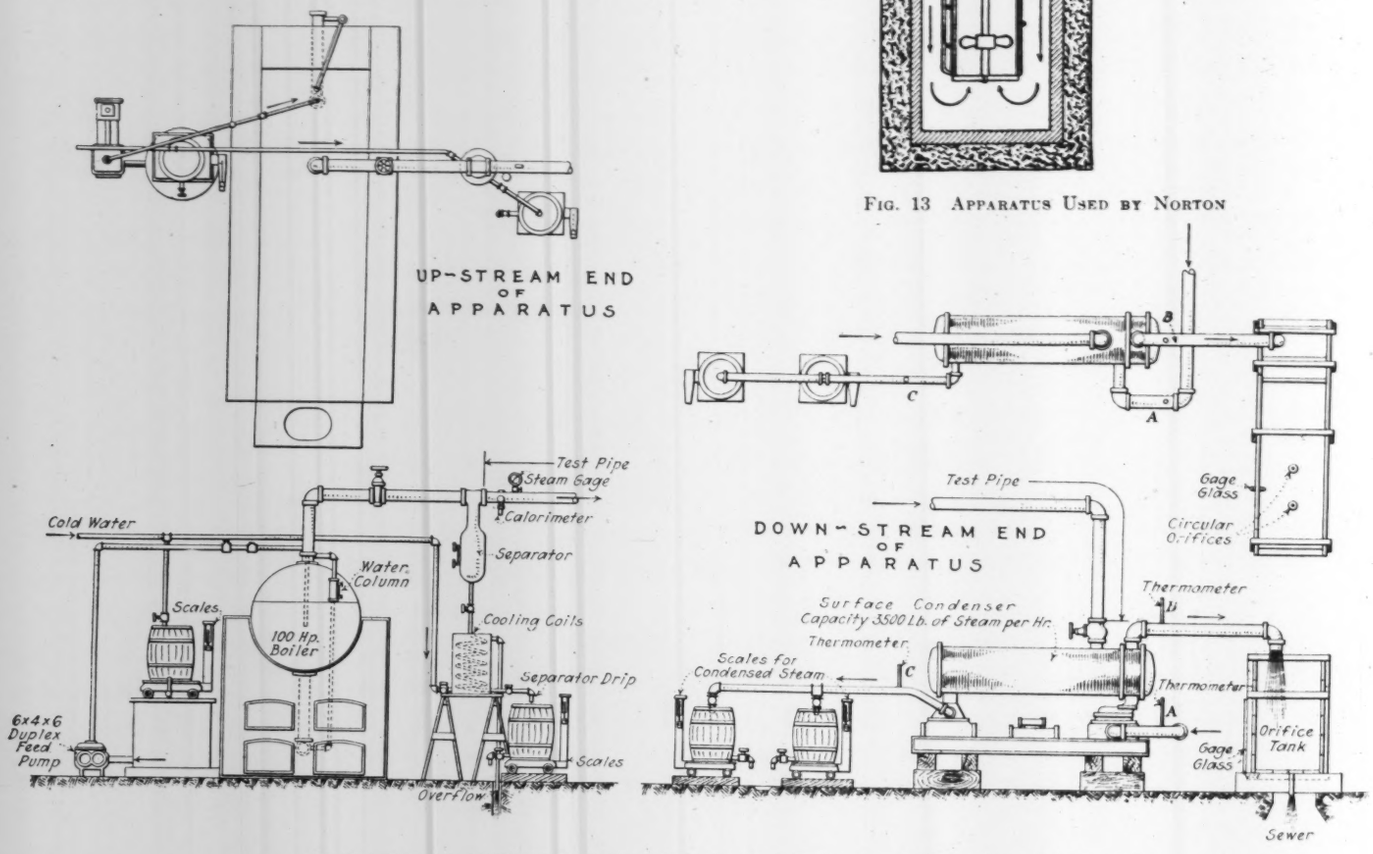

Fig. 12 Method Used by Gasche in Determining Efficiency of Pipe Coverings

Appendix—Bibliography

THE few items here listed are only a small portion of the total literature and include only articles in which descriptions of apparatus for the testing of other than flat surfaces are included.

The author is responsible for such critical notes as are included and will welcome correction where his judgment is in error.

REVIEWS OF INVESTIGATIONAL WORK

1 Péclet, Eugene, Traité de la Chaleur. Part of his work has been translated by Paulding, Chas. P., Steam in Covered and Bare Pipes, published by D. Van Nostrand Co., New York, 1904.
Describes methods used by Péclet as far back as 1841 on the determination

of the conductivity of many materials and the determination of the emissivity of various surfaces, separating the surface losses into radiation and convection. Péclet studied the effect of diameter and height of cylinders upon the loss of heat due to convection. While his work was very thorough and complete in the temperature range with which he worked, his apparatus could not be applied to practical testing of steam-pipe coverings at the higher steam pressures common today. Péclet's work was carried out at very low temperatures and the values obtained by him have been found to be much lower than the values given by later investigators for similar materials.

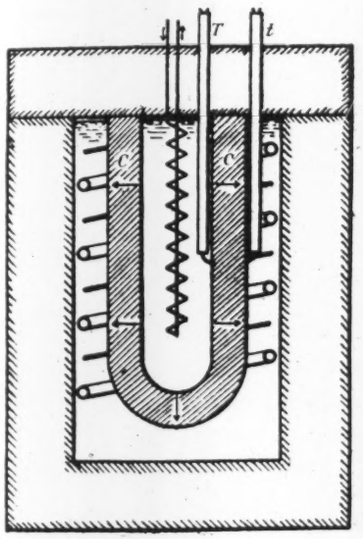

FIG. 14 APPARATUS USED BY CARL HERING

2 Ordway, J. M., Non-Conducting Coverings for Steam Pipes. Trans. A.S.M.E., vol. 5 (1884), pp. 73 and 212; and vol. 6 (1885), p. 168.

Ordway conducted an exhaustive series of tests on practically every known heat insulator at that time. The apparatus recommended and used mainly by him consisted of a calorimeter constructed from brass which was placed over the pipe covering while it was in place on the test pipe.

In making tests, the calorimeter was filled with water 50 deg. fahr., colder than the air of the room, thermometers were inserted, and the water was well agitated with paddles. The temperature of the water, the steam pipe, and the air of the room, and the time were noted down. Observations were made every half-hour or oftener, till the water became 50 deg. fahr. higher than the temperature of the surrounding air. The water was then drawn off and weighed. The experiment was repeated several times to get a fair average.

3 Jamieson, Andrew, Determination of the Thermal Conductivities of Heat Insulators. Proc. Inst. C. E., vol. 71 (1894), iii, p. 291.

The apparatus used consisted of three cylindrical tin cases. The first or innermost was 6 in. in diameter and was filled with 10 lb. of hot water. The second vessel which contained the first was 8 in. in diameter. The nonconducting material under test filled the space, of 1 in. thickness, between the outside of the first and the inside of the second case. The third or outer vessel was 10 in. in diameter and formed the water jacket for the first and second cylinders and the material under test between them. Each vessel was made waterproof from any of the other vessels. Unquestionably considerable error was involved in an apparatus such as this.

4 Brill, Geo. M., Pipe Covering Tests. Trans. A.S.M.E., vol. 16 (1895), p. 827; also *Power*, Aug., 1895, pp. 8–9.

The condensation method was used in these tests. Approximately 60 ft. of standard 8-in. wrought-iron pipe was suspended about 10 ft. above the floor of a large room. The steam used was sent through a separator on its way to the test pipe, and in the short connection between the separator and the pipe a throttling calorimeter was placed. The test pipe had an inclination of 1 ft. in its entire length, which insured drainage of all water of condensation into the receiver at the other end. The receiver consisted of 4 ft. of 12-in. pipe, with graduated water glasses attached near the top and bottom.

5 Gasche, F. G., Experimental Determination of the Efficiency of Pipe Coverings. *Power*, Dec. 1896, p. 14.

The condensation method was used. These tests, however, differ from the usual condensation tests in that no dead-end pipe was used. The pipe covering undergoing test was placed on an 8-in. steam line 200 ft. long. Live steam was passed through this line and was condensed by a surface condenser having a capacity of 3500 lb. of steam per hour. The amount of heat passing through the covering was determined by measuring the heat entering and leaving the test pipe, the difference between the two giving the heat passing through the covering.

This method should give very good practical test results, but, like all other condensation methods on long steam lines, requires considerable time and is very expensive. The apparatus used is shown in Fig. 12.

6 Norton, C. L., The Protection of Steam Heated Surfaces. Trans. A.S.M.E., vol. 19 (1898), pp. 729–753.

The apparatus used is shown in Fig. 13 and consisted of a piece of vertical steam pipe, heated electrically from within by means of coils of wire in oil.

7 Lamb, C. J., and Wilson, W. G., The Conductivity of Heat Insulators. Proc. Royal Society of London, vol. 65 (1899), p. 283.

The method employed consisted in placing the material under test in the space between two cylindrical copper pots, kept at a definite distance apart by pieces of vulcanized fiber; the inner pot contained a small motor with a fan attached to the axis; a tin-plate cylinder open at the top and with holes at the bottom was placed inside to direct the currents of air over the inner surface of the inside pot. Energy was supplied to a heating coil within as well as to the motor. The outer pot was then immersed in a tank kept overflowing from a water main. The temperatures were measured by means of thermoelectric junctions of copper and iron.

This apparatus can be used for very low temperatures only, as the temperature of the inner vessel cannot be raised above the temperature at which the insulation of the motor would burn out. Possibly fairly accurate results can be obtained with this apparatus for cold-storage insulation.

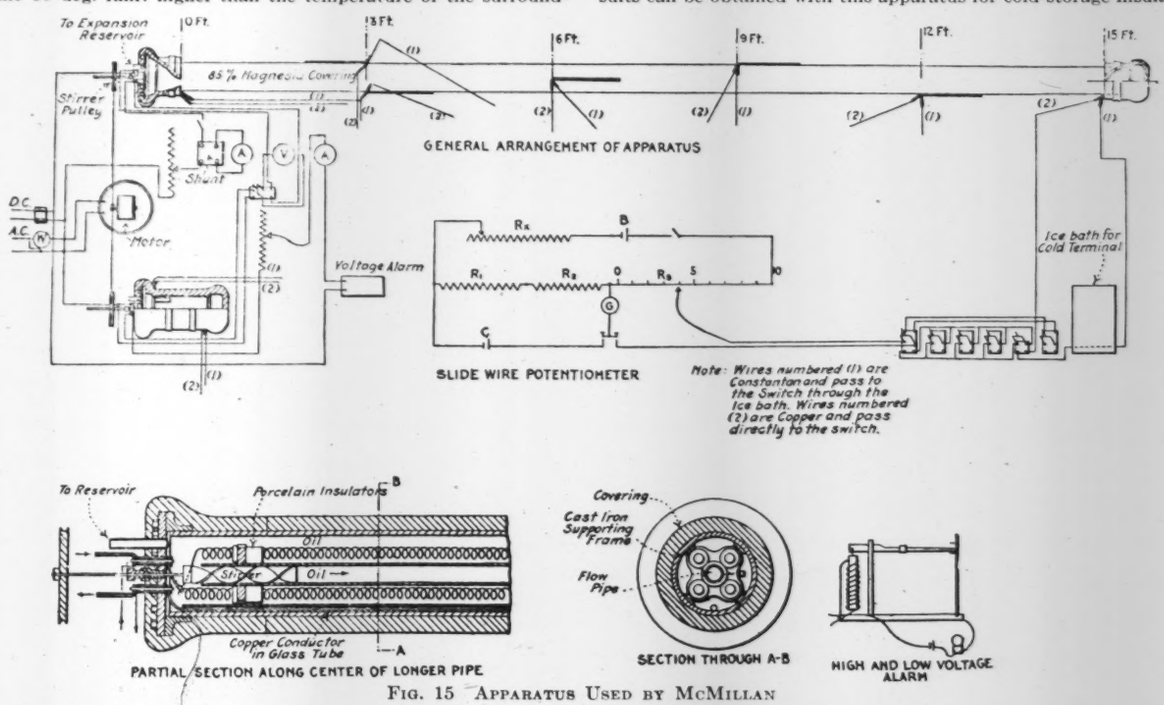

FIG. 15 APPARATUS USED BY MCMILLAN

8 Jacobus, D. S., Tests of Non-Conductive Coverings for Steam Pipes. *Stevens Institute Indicator*, vol. 18 (1901), p. 240.

In the condensation method employed four similar 2-in. steam pipes each 12 ft. 2 in. long were used to determine the efficiency of various coverings placed on the pipes at the same time.

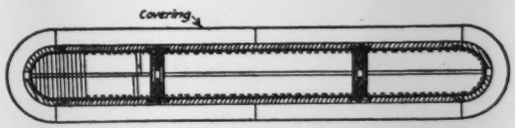

FIG. 16 APPARATUS USED BY BAGLEY

9 Stott, H. G., Steam Pipe Covering and Its Relation to Station Economy. *Power*, Dec., 1902, p. 33.

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The test pipe consisted of 200 ft. of 2-in. pipe heated electrically by means of a heavy current passing through the wall of the test pipe itself. Sections 15 ft. long were marked off and potential leads were soldered to the pipes 2 ft. from each mark, making the length of covering under test equal to 11 ft. The various coverings under test were placed on the pipe at the same time and the heat passing through was determined from the voltmeter and ammeter readings.

The main objection to this method is that the high conductivity of the iron pipe would have a tendency to equalize the temperature of the pipe throughout its entire length. Also the method used in measuring the temperature of the pipe was probably not very accurate.

10 Barrus, George H., Tests of Steam Pipe Coverings. Trans A.S.M.E., vol. 23 (1903), p. 791.

The author used the condensation method. The coverings were tested on 2-in. and 10-in. pipe. The tests, as a rule, were made without circulation of the steam other than that produced by the effect of condensation. To determine the effect on the efficiency of the covering where the pipes contain steam in a quiescent state, or where the steam is moving with considerable velocity, the drip ends of two of the test pipes were provided with means for establishing a current of steam through the pipe without carrying away any of the water of condensation; and tests were made in each of these pipes under each condition, there being first a period with the steam in its quiescent state, and then one immediately following during which a measured quantity of steam was drawn off and the test repeated. The results of these tests showed that there was no difference whatever between the rate of condensation whether the steam was in circulation or practically quiet; or if there was a difference, it was so slight as to be within the limit of probable error of measurement.

11 Nusselt, Wm., The Conductivity of Heat Insulators (German). *Zeitschrift des Vereines deutscher Ingenieure*, vol. 52 (1908), pp. 906–912 and 1003–1006.

Nusselt's method consisted in ascertaining the temperature distribution through the insulating material when it was placed between two concentric sheet-copper spheres, the inner sphere being heated electrically. In some of the tests a cube was substituted for the outer sphere.

The apparatus used probably gave very accurate results. Nusselt claims an accuracy in temperature measurements of from 0.3 to 0.5 deg. for low temperatures and 1 to 1.5 deg. for high temperatures. His apparatus lends itself to the testing of powdered materials and materials which can be made into a mortar, but it could not be used satisfactorily for the testing of cylindrical shapes.

12 Hering, Carl, Methods for Determining Thermal Conductivities. Trans. Am. Electrochemical Soc., vol. 18 (1910), p. 213.

Describes a cylindrical cup, with its one end rounded off to a hemisphere, the other end being flat and covered with a flat piece of insulating material. The inside of the cup contains a heating liquid provided with a heating coil; the insulating material is placed between the two metal walls of the cups and a cooling liquid surrounds the outer cup. Thermocouples are placed in each of the two walls of the cup to measure the temperature drop through the material.

This apparatus, shown in Fig. 14, is suitable only for measuring the thermal conductivity of powdered materials or materials which can be made into a mortar and placed between the two cups. The accuracy of this instrument is probably not very high, as it would be hard to estimate the loss through and around the insulating cover at the top.

13 McMillan, L. B., Heat-Insulating Properties of Commercial Steam-Pipe Coverings. Trans. A.S.M.E., vol. 37 (1915), p. 921.

The test pipe used was a 16-ft. section of standard 5-in. steel pipe closed at the ends and filled with gas-engine cylinder oil. It contained resistance coils which served as an electric heater and a stirring device for keeping the oil in circulation.

About 5 in. at each end of the test pipe was covered with 85 per cent magnesia, leaving 15 ft. of the central portion of the pipe as the test section. The remaining surface of the ends was covered with plastic 85 per cent magnesia. The end correction was accomplished by the use of a short pipe which was a reproduction of the two ends of the test pipe. This short pipe was covered in the same way as the ends of the test pipe. When the ends of the test pipe were at the same temperature as the short pipe the loss should be the same for both test pipe and short pipe. Therefore the difference between the loss from the test pipe and that from the short pipe should represent the loss from the 15-ft. section of test pipe covered with five standard lengths of commercial covering.

The main objection to this method is the inability to vary the end temperatures of the test pipe so that the ends may be considerably lower or higher in temperature than the central portion of the test pipe. Also there is a possibility of error in not having the same thickness of magnesia and not having magnesia of the same conductivity value on the short pipe and on the ends of the test pipe. The errors due to these causes would be greatly increased when a shorter section of test pipe than 15 ft. is used. Several test pipes of somewhat similar design having a test section of 6 ft. in length are now being used. The apparatus described is shown in Fig. 15.

14 Bagley, Glen D., The Conservation of Heat Losses from Pipes and Boilers. Trans. A.S.M.E., vol. 40 (1918), p. 667.

The test pipe used consisted of three pieces of 3-in. standard steel pipe, the middle section being 3 ft. long and each end section $1\frac{1}{2}$ ft. long. The sections were connected by heat-insulating disks of asbestos board and each end section was provided with a hemispherical cap of cast iron. Inside of each section was an electric heater made by winding resistance wire on a frame of asbestos boards. The wires were finely spaced and close to the inner surface of the pipe. The end correction was applied by varying the current input to each heater until the temperature of the pipe over the end sections and the central section was the same in each case; then, since there was no temperature difference there could be no endwise flow, and the heat supplied to the central section passed out radially through the pipe and covering undergoing test.

The main objection of this apparatus (shown in Fig. 16) was the fact that no heat could be supplied at the junction of the ends and central portion of the test pipe, with the consequence that the asbestos-board heat insulators were at a lower temperature than the pipe adjacent to them, resulting in slightly uneven temperature distribution throughout the test pipe.

15 Thomas, R., The Thermal Conductivities of Insulators in Relation to the Lagging of Steam Pipes. *Chem. & Indus.*, 38, no. 19, Oct. 15, 1919, p. 357.

The apparatus used by Thomas consisted of a copper can about 8 cm. in diameter and 10 cm. in height. Two holes 1 in. in diameter were drilled opposite one another a little below the center. Two rubber stoppers carrying a thin copper tube of 19 mm. internal diameter were inserted in the holes. Another thin copper tube, of 12.2 mm. external diameter, was placed coaxially inside the 19-mm. tube and kept in position with rubber stoppers. The space between the two tubes was filled with the material whose conductivity was to be measured. Superheated steam of known temperature was passed through the inner tube, and the rise in temperature of a known weight of water placed in the can was determined during a definite interval of time.

No data are given as to how the temperature of the superheated steam was measured, and since there was possibly considerable drop in temperature from the steam to the insulating material, considerable error would necessarily result. No data are given as to how corrections were made for radiation and end loss. This apparatus could be used only as a very rough determination for powdered materials, and could not be used for pipe-covering testing.

16 Dana, H. J., Commercial Efficiency of Single and Graded Steam Pipe Covering. *Engineering Bulletin* No. 12 (1923), State College of Washington.

The test pipe used was a standard 5-in. steel pipe about $15\frac{1}{2}$ ft. long, closed at the ends and filled with oil. An electric heating element was wound on a 2-in. pipe and placed inside the 5-in. pipe. The oil was kept in motion by means of a motor-driven stirrer.

The ends of the test pipe were covered with plastic magnesia cement. Approximately twelve $\frac{1}{4}$-in. holes were drilled perpendicularly into each end coating of cement, and in these were inserted alternate junctions of a number of thermocouples connected in series. The remaining and opposite junctions were left against the outside surface of the cement. Over this was applied another coating of magnesia cement about $\frac{1}{4}$ in. thick, and to the surface of this was applied a pancake heating element, which in turn was covered with a final coating of plastic cement. When the current to this auxiliary heater was properly adjusted the temperature at the heater element was the same as the temperature at the surface of the end of the pipe, and there would then be no transfer of heat, or end radiation. This condition was determined by a zero reading of the thermojunctions connected in series.

Status of Heat-Transmission Data and Knowledge in the Refractory Field

General—Requirements of Practical Engineering—Data Available for Engineering Problems and a Review of the Literature Therefor—Conclusions

By P. NICHOLLS,[1] PITTSBURGH, PA.

THE field of heat transmission to be covered in this report is that in non-metallic materials which are used in connection with temperatures in excess of 1000 deg. fahr., say, that is materials which are generally classed as being in the refractory field.

The factors that separate this field of heat transmission from others are, first, that the temperatures necessitate a decided change in the testing apparatus; second, that the materials are liable to be materially affected by the temperatures to which they are subjected; and third, that since the range of temperatures is large the change of conductivity with temperature, that is, the temperature coefficient, becomes of more importance than with materials used in the steam and lower-temperature fields.

The object of the report is (*a*) to review the state of knowledge of this subject which practice would seem to need, now or in the future; (*b*) to examine the extent and probable accuracy of that now available; and (*c*) to deduce what is missing and to suggest what should or might be done to obtain it.

General

Refractories and their applications have taken an important place in research during recent years. The efforts to procure increased and more economical production have tended to raise the temperatures used in manufacturing operations, and the limit to the improvement possible is often fixed by the ability of the refractory to last an economical period. As a consequence the walls or structures are liable to suffer considerable deterioration and change. Also the refractory material exposed to the furnace or which is in contact with the process material is fused, eroded, and often changed to an appreciable depth by fluxing, or is chemically changed by combining with the process materials, the slags, or the vapor given off by either.

Heat-transmission investigational work which is to be applied to engineering problems cannot neglect these practical factors, and though their proportional importance in the overall flow through a thick wall may be small, yet the thermal-transfer constants will undoubtedly play some part in the rate of deterioration.

It must also be recognized that small differences in the thermal-transfer constants are of minor importance compared with the ability of the refractory to stand up in service.

Requirements of Practical Engineering

This field may itself be subdivided into—

A—Materials which are used distinctly for heat insulation, that is, are not subjected to the highest temperatures, but are placed on the cooler side of the true refractory part of the furnace. Such materials are, in general, commercial insulations which have little strength, or ability to stand abrasion.

The materials which can be used are fixed by the temperature to which they will be subjected. Those able to stand a maximum temperature of 1400 deg. fahr. (766 deg. cent.) will meet most conditions, but a claim of being able to withstand 1800 deg. fahr. (986 deg. cent.) is made for preheated and shrunk infusorial earths.

B—True refractory materials which can be subjected to the furnace conditions. These are used for two distinct purposes:

a To merely serve as a container for the furnace, and therefor, other things being equal, the higher heat-insulation value they have, the better the economy. To this class belong all furnace and boiler walls.

b To transmit through them the process heat and in some way to contain or support the process materials. Thus, other things being equal, the higher thermal conductivity they have the better they serve their purpose. To this class belong all muffles, melting-pots, saggers, coke-oven walls, etc.

The temperature to which they may be subjected in service can be placed as 1500 to 3000 deg. fahr. (850 to 1650 deg. cent.), but it is probable that a maximum temperature of 2800 deg. fahr. (1500 deg. cent.) for heat-transmission tests would meet all requirements.

C—A third important practical class of heat transference which falls into this field is the flow through aggregates, that is, through the process materials themselves, such as ores in roasting or smelting, clays during burning, coal during coking, and shale in distilling.

In discussing any engineering technical requirement it must be recognized that not only are data desired on the physical laws and materials used, but that there must also be an equivalent order of accuracy on the ability to define and give values to the "conditions." (This term will be used in this report to include all the factors associated with or causing the action being discussed, such as temperatures and their variation, time of firing, deterioration of materials, etc.; also the materials themselves through which the heat transference occurs.) As far as this ability is lacking it is equally important to obtain data for it.

Heat-Flow-Prevention Class. Classes A and B (*a*) can be treated together, as they, in general, cover heat transferred through boiler, furnace, and kiln walls, roofs, and floors. They were well covered by Hull (see Appendix, R-1). The main present practical need is to be able to predict the heat loss for economic reasons, to determine whether the loss could be profitably reduced. As this brings in commercial features, it has naturally been the underlying reason for much of the investigational work which has been done, and there is more general literature on this phase than on any other.

The total amount of fuel which is lost through such transference is large, and as much should be saved as the true economic principles will permit. The word "true" is used because facility to repair or replace, and the effect of temperature or temperature gradient on the refractory must be included. As to how near usual estimates of such losses are to those which occur the author could not state, but as far as they are out it is probably mainly due to incorrect assumptions of mean temperatures, or inaccurate averaging to save computation. Generally speaking, no very close knowledge of the thermal transference is required for this purpose at present, since conditions are often uncertain, future mode of operation not known, and the true economics not settled.

To be able to make a close prediction the following will be required:

a Ability to predict thermal coefficients from other physical qualities

b Full knowledge of the furnace-wall inner-face temperatures from the type of heating

c Ability to translate cycles of operation into an average

d Ability to average the heat loss for the life of the installation, or between replacement periods

e Such tables or simple formulas as will permit of sufficiently accurate computation for complicated conditions or cycles, without using the mathematics rigidly required.

In addition to the economic there are the following other practical requirements which necessitate knowledge of the thermal coefficients:

a Ability to predict the outside temperature of furnace walls, or of the surrounding floors. These of themselves can be a measure of the heat dissipated. Provided the thermal coefficients and con-

[1] Heat-Transmission Engineer, U. S. Bureau of Mines.

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ditions are known, the wall problems can be solved easily, but the floor ones are more complicated, and they both become so when the conditions are cyclic

b Ability to predict the resulting temperatures of the air and surrounding bodies

c Ability to predict the temperature gradient through the wall, and particularly through the hotter part of it

d Ability to predict the temperature of supporting metal work

e Knowledge of air, gas, and vapor leakage, and its effect on wall temperatures. This is a subsidiary action but is probably of great importance in the study of refractories, and will affect the temperature gradient. The total heat transfer caused by leakage may be considerable in large furnaces or kilns, being accentuated when it is difficult to keep the brickwork free from cracks

f Ability to determine the heat lost from doorways or openings, either with or without covers.

Attention is again called to the fact that correct data on the thermal constants are not the only factor, but that there must be ability to predict or determine values for the conditions, and there must be available a correct mathematical treatment either directly or by averaging formulas.

Heat-Flow-Encouragement Class. This covers class B (*b*) and the necessity of using a comparatively poor conduction material, like the best of the refractories, is an unfortunate limitation fixed by the temperatures needed for the processes.

There has been little demand for thermal data for engineering problems involving flow through muffle and similar walls, although undoubtedly it is highly important. The reasons for this are probably three. First, the processes are usually old and the operators have obtained their working data of temperatures and times from long experience and many extended service trials. Second, the heat transfer through the refractory container is only one portion of the action, and that into and through the process material is equally important. Third, the many variable factors, and the difficulties of computations, even assuming the thermal coefficients are known, are so much greater than those for furnace walls that the trades have considered that their own experience is more dependable, and investigators have naturally preferred to keep to the simpler problems, or have not had the opportunity or money to take these up.

There is every indication that these attitudes are changing, and that a more intimate knowledge of the sequence and magnitude of events is being desired, both to permit of more definite regulation and better manufacturing economy, and in order to obtain better fuel economy.

Although this and the next classification of heat transfer through aggregates are part of the one transfer, yet that through the refractory is to a large extent open to separate investigation.

The engineering information needed is thermal constants and formulas to predict the rate of heat transfer into and through the refractory casing, and its relationship to time. This can be divided into its two components of the transfer to the outer surface, and that through the refractory. The former will often involve rather indeterminate conditions, and, generally speaking, there are few data available. The latter is simplified in that the refractory can usually be depended on to be of uniform manufacture and definite dimensions, but to offset this it may become contaminated with the process material. Also both are complicated due to the operations usually being cyclic.

The transfer from the inner surface to the process material is bound up with a variety of conditions in that there may or may not be direct contact between them.

Heat Transfer into and Flow through Aggregates. This refers to class C, and covers roasting, smelting, melting, and coking operations. As far as the author is aware, no investigational work has been done for this field, but naturally there must be a large amount of overall data in possession of the various trades.

There are two general classifications of heating methods:

A—The material is enclosed in a container, when the transfer will be by the following means:

a Direct conduction from the sides and between the pieces

b Radiation from the container walls and between the pieces

c The natural convection of the gas or vapors

d The transfer due to evolved gases or vapors.

B—The material is heated by passage of a stream of heated gas through it.

In both methods the main factors, other than thermal coefficients and temperatures, that enter into the problem will be:

a Size, shape, and percentage of voids

b Exothermic and endothermic reactions in the material

c Change in the aggregates due to the process

d Heat transfer by the evolved gases.

At present we have no fundamental data from which we could predict internal temperatures through the mass. As previously stated, each trade will have its own experience, but it is doubtful whether this could be applied to predict the effect of changed conditions.

It is evident that investigational work on heat transfer would usually be more economically done in conjunction with other process research. In spite of that it would seem reasonable that engineers should ask that fundamental data might be available, at least for aggregates which are not changed by the heating.

Data Available for Engineering Problems

Provided we have the correct values for the "conditions," and for the thermal coefficients, then we can solve any engineering problem that permits of a mathematical solution, or can obtain approximately true results for the others. It may be quite laborious to calculate results for a complete structure in which the conditions vary from place to place, or change with time, but close approximations are possible. Also conditions in general must be determined by investigation, but since these vary with each engineering application, they are not under detail consideration here, having been sufficiently discussed in the previous sections.

The mathematics are available for conditions which involve only constant heat flow, and there should be no difficulty in having this portion of the work correct, provided a structure is divided up into a sufficient number of parts to cover varying materials, change in structure, or temperature changes. It seems possible, however, that engineers could be further assisted by formulas or tables which would at least take care of the average type of variations which occur in standard constructions and conditions.

The mathematics for problems in which the conditions are cyclic, or for which values are required to be plotted against time, are more complicated, and there is still more reason here why some attempt should be made to reduce to tables such of the problems as may be of common occurrence.

The most definite data existing cover the thermal properties of refractory materials—namely, their thermal capacity, conductivity, and diffusivity. Published values differ materially and investigators have obtained results for nominally the same material which differ by 100 per cent. The possible justification for such difference will be discussed later, but it is quite reasonable that engineers should ask which they may take as being correct.

It is also reasonable that if a material of a given name or designation may have values that differ considerably, then engineers should expect that they should be able to fix its thermal coefficients fairly closely by measuring physical qualities other than the thermal, due to the difficulty and expense in determining the latter.

Knowledge of the accuracy of computation of the heat transfer to and the resulting surface temperature of the inner walls of a furnace is not assured. Available test data are very meager, and the ability to define gas temperatures and other factors needed for computations is small. The literature on furnace temperature conditions is scattered and requires coördination.

Even supposing experimental laboratory work were done under controllable conditions, their application to practice would be doubtful due to the variations in temperature of the gases through the mass, the partial dependence of the radiation on the amount and temperature of the hot suspended particles, and to the uncertainty of the velocity and temperature of the hot gases adjacent to the refractory surfaces.

Review of Literature for Data Available

The literature may be classified as follows:

a Original research on thermal coefficients

b Reviews of research results

c Consideration of conditions causing, or under which, heat

transfer occurs, and application of thermal data to engineering practice

d Economic consideration of the heat transfer

e General literature.

Items *c*, *d*, and *e* will not be considered. The Appendix to this report lists and briefly reviews the majority of those under item *a*, and a few under *b*. Since our interest is in the thermal coefficient, the former will be shortly summarized, but interesting reading is usually to be found at the start of each paper, since each investigator reviews previous work and justifies his departure from former methods.

All the research work at high temperatures has been done during the past 18 years. The following methods used are based on one of three principles:

A—To determine the thermal conductivity by establishing constant heat flow and temperatures. A parallel-faced slab, a hollow cylinder, or a hollow sphere has been used as the test piece; the surface temperatures only may be observed and thus obtain a mean conductivity, or they may be taken at intervals in the direction of the heat flow, thus getting data to determine the variation of conductivity with temperature. The cooler surface may have air exposure, or a high or low temperature may be enforced on it by a heating or cooling plate.

B—To quickly bring one side to a fixed high temperature, and to observe that at another point in the line of heat flow. The diffusivity is then calculated from the change in the latter temperature with time.

C—To apply a cyclic temperature having a sine value with time at the hot face, and observe the temperatures at two points in the line of flow. Then to calculate the diffusivity from the phase or amplitude difference of the two temperature curves.

To deduce the thermal conductivity from the diffusivity of methods C and B it is necessary to know the specific heat. This changes with temperature and its determination at high temperatures is difficult. The same difficulty occurs when the diffusivity is deduced from the conductivity obtained by method A.

Only two investigators used method B (R-1 and R-13, Appendix), and one C (R-14), the others all used some form of method A. There is no reason to condemn B and C, in fact, there is much in their favor.

Granting there can be one and only one true value for the thermal conductivity of a given material, it is reasonable to assume that the disagreements are due to one or more of the following causes:

a There were investigational errors

b Although the samples of a given material used by the different investigators were apparently nearly the same, yet there were actually different physical characteristics that materially affected the thermal properties

c There was some other heat-transfer action taking place, such as air filtration, which was not recognized by the investigators. It is, however, decidedly improbable that such a volume of air could have been flowing through the sample as to cause such differences.

A recent paper (R-17, Appendix) suggests another possible explanation, in that their results show that the conductivity coefficient varies greatly with the rate of heat flow, at least for carborundum. Since this seemingly has no explanation (except for minute changes with porous materials), and since it is contrary to the fundamentals on which all heat-flow principles depend, it would be necessary to have very positive proof before it could be accepted.

A comparison of the values obtained by investigators might be misleading unless it were accompanied by all the specifications of the materials used. However, to convey some idea of their range, the thermal conductivities have been picked out or approximately deduced for three materials which the specifications given in the papers indicate to be approximately the same. The conductivities were chosen for 800 deg. cent., and are in C.G.S. units, cal. per sec. per sq. cm. for 1 deg. cent. per cm.

It will be noted that the values for fireclay do not differ as much as do those for the other materials. This is some indication that the greater differences are probably due to the samples tested, since fireclay is more liable to be similar at different locations.

All the investigators seem to have done careful work, and it would be difficult to find positive reasons for discarding individual values.

	Fireclay	Silica	Magnesite
Dudley, R-11	0.0031	0.0033	....
Dougill, R-9	0.0035	0.0039	0.01
Goerens, R-10	0.003	0.0034	0.0087
Heyn, R-8	0.0019	0.0018	0.0013
Van Rinsam, R-12	0.0022	0.0027	0.0038
Green, R-13	0.003	0.0034	0.0087
Tadokoro, R-14	0.0037	0.0054	....
Hersey, R-15	0.0025	....	....
Beecher, R-16	0.0022	0.001	0.0065[1]

[1] At 1000 deg. cent.

An engineer would probably give more weight to those tests which used full-sized samples of commercial materials, and for this reason those of Dudley and Dougill have been in favor in recent years. On the other hand, the most thorough and painstaking is undoubtedly that of Tadokoro, particularly in the measurement and record of the other physical qualities. It is the one investigation in which two of the methods last named (A and C) were used to check each other. In spite of the fact that the record shows that the conductivity deduced from the two values do not differ more than one per cent each for 5 different types of materials, yet one would hesitate to give preference to his values, particularly at the higher temperatures.

In addition to the bibliography given in the Appendix, a number of other investigators have measured the temperatures in furnace walls. Since the rate of heat flow was not measured, the thermal coefficients cannot be deduced, and though the investigations are informative they do not help in the present analysis.

In the literature survey one does not find more than one report by any one investigator, or even from any one institution. That the institution did not continue the work would indicate that it has often been financial reasons that have caused the stoppage. The benefits from the knowledge gained would rarely be direct, and financial support hard to obtain. At least it is unfortunate, and certainly it is inefficient and uneconomical. One would have expected that each new investigator, starting out with the honest belief that he was going to overcome the defects in the methods used by his predecessors, would desire to try every scheme to deduce additional data to give his results a preferential importance, or that he would at least have made an endeavor to obtain duplicates of the samples used by another. This lack of continuity of work would seem to have been the chief weakness.

The large drop in temperature that may occur at air gaps and joints of compound walls is often not recognized, and there is need of more data and computation rules.

Conclusions from the Analyses

The object of attempting to draw conclusions is to evolve lines of action for the concerted movement on heat transmission inaugurated under the National Research Council.

The author fully agrees with the general conclusions reached in the excellent review of the subject by Hull (R-1) and has endeavored to bring that out in the text of this report, namely, that the uncertainty about and the variability of the conditions of practice do not warrant attempting very exact computations, nor are small disagreements in the values for the thermal coefficients of a given class of engineering material of importance.

In spite of this it is desirable that pure-research work should be done to determine the reasons for and magnitude of variations, since this is always of assistance in shortening and helping to explain and classify overall tests.

Thermal Coefficients of Materials. Before more work is undertaken there should be a broad plan which will assure its continuation under the same auspices.

It would seem desirable that the initial attack should be on one material in all its possible physical forms.

It would seem very desirable that there should be available some one material whose uniformity and similarity in different samples is so assured that it could be used by investigators as a common check piece for comparisons of methods.

The final test of the accuracy of values for engineering application is that results in service should agree with those predicted from laboratory tests. Any plan of attack should include the measurement of the flow in service of the same refractories as tested in the laboratory.

Surface Actions at High Temperatures Between Gases and Solids. The author believes that there is scope for large-scale laboratory

work to determine radiation constants for gases with various compositions, and carrying solids and burning particles. Physicists have been extending the knowledge of flames and flame temperatures.

It is, however, very probable that more efficient work could be done by accumulating data from actual furnaces. The importance of this factor on the heat loss through the wall is not great when compared with the uncertainty of operating conditions. On the other hand, it is important in connection with heat transfer to water-cooled surface, and data collected for that purpose are of the same order as those required for the wall losses. Commercial organizations are undoubtedly obtaining such data, and it would seem that a central committee could collect those which are available, classify them, make them available, and act as a reference to assist investigators.

Mathematics of Heat Flow. The text has suggested that as far as engineering computations connected with heat transmission in this field are in error, it is probably more often due to inadequate mathematics or incorrect averaging. There would seem to be an opportunity to help practicing engineers by constructing tables and formulas for some of the standard problems. This could only be done after a careful and extended survey of the particular structures in operation.

It seems to the author that the most useful help will be derived from field observations. As far as a central committee, well acquainted with the industries, could be in touch with all work going on, and with all aspirations to make observations, it would be in a good position to coördinate it, save the time and money of the investigators, and adapt the results to the most useful form for others.

Appendix—Bibliography

THE few items here listed are only a small portion of the total literature, and only include the original records of investigations. Incomplete investigations which merely compare materials, and those covering temperature measurements only, are not included, nor are articles of an economic or general nature.

The author is responsible for such critical notes as are included and will welcome correction where his judgment is in error.

Reviews of Investigational Work

R-1—Hull, W. A. (Bureau of Standards), The Status of Thermal Conductivity on Specifications. Proc. A.S.T.M., vol. 22 (1922), pt. 1, p. 309.

A very good and practical review of the present engineering requirement for data on the subject, more particularly for furnace walls. The writer concludes that the work of Dougill and of Dudley (R-9 and R-11) gives values sufficiently accurate for the needs at the time of writing. He emphasizes the need of standardized test methods.

R-2—Rosin, P. (German), The Fundamentals of Heat Losses in Metallurgical Furnaces. *Metall. u. Erz.*, vol. 18 (1921), pp. 37–45, 78–88, and 99–104.

A detail metallurgical consideration of heat losses, and consideration of existing values and tables. (Not reviewed by author as it was not available.)

Furnace-Wall Insulations

There is a large number of general and economic articles on this subject, but the majority of them are not based on tests at higher temperatures. As far as insulations used in the steam temperature field can be used for furnace walls, there are additional articles containing good information.

R-3—Griffith, E. (National Phy. Lab., England), Thermal Conductivity of Materials Used in Furnace Construction. Trans. Faraday Soc., vol. 12 (1917), pp. 193–206.

Reviews past work and describes a method in which one side of the sample is immersed in molten tin kept liquid by a heating coil and the other cooled by a pipe coil through which water is circulated and its temperature change measured. For temperatures above 930 deg. fahr. (500 deg. cent.), a muffle wall was used as the hot temperature. Work was mainly confined to refractory insulations. There seems to have been no definite objective in the work.

R-4—Horning, R. H. (Armstrong Cork Co., Pittsburgh, Pa.), Heat Transmission of Brick and High-Temperature Insulation Materials. Trans. Am. Ceramic Soc., vol. 3 (1920), p. 865.

Used constant-flow method with center electrically heated coils of wire. There were three heating coils covering 20 in. by 20 in. area, the center $6^3/_4$ in. sq. area being used for the heat-flow and temperature measurements, by measuring the drop in voltage on this length of the center coil. Cold plates were used on both sides of the test samples, and the whole surrounded by insulation. Allowed 36 hours to attain equilibrium. Tested magnesia, silica, fire, and vitrified building bricks, as well as insulations. Obtained a positive temperature coefficient for the magnesia brick. It is questioned as to whether the order of accuracy could be guaranteed, because of the lack of even distribution of the source of heat. The thermal conductivities in C.G.S. units at a mean temperature of probably 450 deg. cent. figure out as: Firebrick, 0.0013; silica, 0.0023, magnesia, 0.0049.

R-5—Calvert, R., and Caldwell, L. (Celite Products Co.), Loss of Heat from Furnace Walls. *Ind. & Eng. Chem.*, vol. 16 (May, 1924), p. 477.

Describes tests using a guarded hot plate 8 in. in diameter, with samples each side and cooling plates outside the samples. The temperatures were measured each side of the test piece and thus the mean conductivity obtained for various temperature differences. As the curves do not give the test points, and as there is no record of checking for instrumental values, it is not possible to pass on the accuracy of the results. Little attempt is made to specify definitely the samples tested. The maximum test temperatures are not given but were probably not over 1300 deg. fahr. (705 deg. cent.). The work seems to have been carefully done and more detail on apparatus and test troubles would be valuable. It gives a short bibliography.

Refractory Investigations

R-6—Wologdine. *Bull. Soc. Encour.*, vol. 3 (1909), p. 879; *Jl. Soc. Chem. Ind.*, vol. 28 (1909), p. 709; *Electrochem. & Met. Ind.*, vol. 7 (1909), p. 383.

This was the first real work on refractory conductivities, but the values obtained now have a secondary rating. Small, specially made samples 5 cm. thick were used and a constant-flow method. Heat was applied below and the transmission measured by a water calorimeter, but there was no use of the guard-ring principle. The maximum hot temperatures were about 1800 deg. fahr. (982 deg. cent.). The work did, however, attempt to connect conductivity with temperature, porosity, permeability to gases, and degree of burning.

R-7—Clement, J. K., and Egy, W. L. The Thermal Conductivity of Fireclay at High Temperatures. University of Illinois, *Expt. Station Bull.*, vol. 42 (1909).

Used a constant-flow method, the test piece being a cylinder with a central heater. The resistance wire of the heater was wound on $^1/_2$-in. tube. The test pieces were 1.4 in. inside and 5 in. outside diameter, and 16 in. long. Thermocouples were placed in longitudinal holes reaching to the center of the lengths.

The test pieces were specially molded, and made from four types of clay mixtures, but no data of the composition are included in the records. The conductivities found are of the order of 0.0025 in C.G.S. units, the mean temperature of test ranging from 400 to 800 deg. cent.

R-8—Heyn, E. (German), Investigations on the Thermal Conductivity of Refractory Brick. *Stahl und Eisen*, vol. 34 (1914), pp. 832–834.

Used commercial bricks and found the diffusivity by applying heat to one face and observing temperatures at points in the direct line of flow. Plotted the curves of temperature against time of these points, and from these determining the diffusivity. His values are low compared with the average by other investigators. A fuller description of this work is given in a communication by Heyn, Bauer, and Wetzel, *Mitt. k. Materialprüfungsamt*, Berlin, 1914, pp. 2–89.

R-9—Dougill, Hodsman, and Cobb (English), The Thermal Conductivity of Refractory Materials, *Jl. Ind. Chem.*, vol. 34 (1915), pp. 465–467.

Reviews the work of Wologdine and Clement and Egy. Used commercial bricks, fireclay, silica, and magnesia, giving good connecting data to other qualities. Used constant-flow method, applying heat at under surface and measuring flow by a guard-ring water calorimeter at the top. Highest surface temperature 2461 deg. fahr. (1350 deg. cent.), but above 900 deg. cent. these were measured with an optical pyrometer. Measured two face temperatures only, but by testing with different hot temperatures deduces the temperature coefficients.

The paper is complete and gives supporting measurements, the weakest point probably being the use of the optical pyrometer without the proof of its accuracy being included.

Tested joint resistances and later in *Gas World*, vol. 68 (1918), p. 269, Dougill gives the result of one test. They noted the change in conductivity that low-burnt bricks show after use, but data in the original paper is not clear as to whether the values there given are for any certain age, nor is it stated as to whether the low-temperature tests were made before or after the high-temperature ones, or as to whether the tests were repeated. Such factors might materially affect the temperature coefficients.

R-10—Goerens, P., and Gilles (German), Thermal Conductivity of Refractory Materials. *Ferrum*, vol. 12 (1915), pp. 1–11, and 17–21.

Used the constant-flow method, heating the hot side by an electrical heater, and measuring the flow by a guarded water calorimeter. The heated part was enclosed by very thick insulation on all but the calorimeter side. Measured the temperature at seven places through the thickness of the test piece (12 cm.), inserting thermocouples in holes drilled at right angles to the flow direction, and to the center of the plate. Tested soft- and hard-burnt clay, slate, limestone, silica, magnesite, and carbon. Maximum temperature about 1832 deg. fahr. (1000 deg. cent.).

The work was of a high order of care, though the upsetting conditions of the holes might be questioned.

R-11—Dudley, B. (State College, Pa.). Trans. Am. Elec. Chem. Soc., vol. 27 (1915), pp. 285–328.

Used a special furnace with a 28-in. by 28-in. removable test section into which the test specimens were built. Measured flow by a guarded water calorimeter at cool side, 8 in. sq. in center with 2-in.-wide guard ring. One test made in a day, with about one hour observation time. Used three sets of holes drilled in the bricks at different distances, the holes being in the direction of the heat flow. Maximum temperatures about 1742 deg. fahr. (950 deg. cent.).

Although these results have been given considerable prominence and the values used, yet there is a lack of confirmatory data in the paper regarding several sources of possible error. The method of measuring temperatures

is liable to give low values, and there is the possibility that constancy was not reached. Since coal was used as a fuel, the constancy of the furnace temperature would be difficult to maintain. Each test was apparently made in one day, and there might be question as to whether constancy was attained.

R-12—Van Rinsum, W. (German, Munich), Thermal Conductivity of Refractory Brick, Steam Pipe Covering, and Masonry. *Zeit. Ver. deut. Ing.*, vol. 62 (1918), pp. 601–605, 639–41.

Used a sphere heater 23 cm. in diameter, and an outer removable shell 60 cm. in diameter. The material to be tested was placed between these, and the outer one then encased with a 45-cm. thickness of kieselguhr. Used maximum temperatures up to 1832 deg. fahr. (1000 deg. cent.), and allowed 14 days to reach constancy. Due to the material being of a special shape there is the question as to whether it is physically similar to that used by other workers. Van Rinsum obtained a positive temperature coefficient for magnesia, instead of the negative generally accredited to it; also the value for magnesia is low. He afterward used the same apparatus for testing various high-temperature insulations, endeavoring in particular to determine the effect of varying the specific density.

R-13—Green, A. T. (English), The Thermal Conductivity of Refractory Materials at High Temperatures. *Trans. Inst. Gas Eng.*, vol. 20 (1921–1922), p. 195.

Reviews previous investigations and adopted the method of suddenly heating one face and measuring rise in temperature at points at fixed distances from it, and at given elapsed times. This gave the diffusivity. He uses values of the specific heat obtained by Bradshaw and Emery.

Maximum temperatures used about 2012 deg. fahr. (1100 deg. cent.). Fireclay, silica, and magnesia bricks as well as a retort material were tested, and several samples of each. Good records of the other physical properties are given.

The work seems to have been carefully carried out, and in the discussion it was stated that the influence of the holes for the thermocouples was shown to be negligible. Corrections were necessary due to the impossibility of bringing the hot face to the high temperature immediately.

There are, however, possibilities of error that are not mentioned as having been guarded against, namely, the initial temperature distribution and reflex waves from the outer surface; also the correctness of the specific heat values.

R-14—Tadokoro, V. (Imperial Univ., Japan), Determination of Thermal Conductivity, Specific Heat, Density, and Thermal Expansion of Different Rocks and Refractory Materials. *Science Reports*, vol. 10, no. 5, 1921.

Used the method of applying cyclic sine waves of heat to the end of the specimen, and obtaining the resulting temperature curves at two points in the line of flow. The lag between or the amplitudes of these temperature waves gives the diffusivity. The samples used for the refractory tests were 4 cm. diameter, 8 cm. long, and temperatures were observed at distances of 5 and 25 mm. from the face heated. The whole sample was heated uniformly to the desired temperature in a special electric furnace, and the cyclic source of heat was applied in addition. The latter gave a temperature range of about 10 to 15 deg. cent. at the first measuring point and about 55-min. cycle.

The whole investigation was most painstaking and thorough. The records on all physical qualities is excellent. The specific heats were determined in order to derive the conductivity, and other observations were made up to 1652 deg. fahr. (900 deg. cent.). It cannot but be believed that there are errors in the specific heats found since these curves all show a rapid and regular increase to between 400 and 500 deg. cent., when they fall off and decrease.

To check the cyclic method, the conductivities were also determined by a constant-flow method, using small cylinders heated in the center by current through a carbon rod. These tests were made at about 100 deg. cent. The table of comparison shows a variation of not exceeding one per cent for six different refractories which, considering that they were different samples and their small size compared with the thermocouple holes, is remarkable.

Although this is undoubtedly the most thorough and complete work done one would hesitate to accept the refractory values, especially at the higher temperatures.

R-15—Hersey, M. D., and Butzler, E. W. (Bureau of Mines, Pittsburgh, Pa.), Conductivity and Specific Heat of Refractories at High Temperatures. Bureau of Mines, *Report* 2564, Jan., 1924.

The apparatus used consisted of an electrically heated guarded plate, an 8-in. sq. center plate and a 2-in. wide guard ring. Similar specimens are put each side of this plate, and against these outer surfaces other heater plates are placed. The whole was surrounded by insulation. With this set-up any desired temperature may be maintained each side of the test specimens and thus, at constant rate of flow, the mean conductivity for a comparatively small range of temperature may be determined.

R-16—Beecher (Research Lab., Norton Co., Worcester), Studies in the Thermal Conductivities of Some Refractory Materials. *Jl. Am. Ceramic Soc.*, vol. 7 (1924), p. 19.

Used the constant-flow method and a generally similar arrangement to that of Dougill (R-9). Sample was 9 in. in diameter of which 3.2 in. was the part actually tested. Heat was applied on the under side, which was a gas furnace, and the flow was measured by a guarded air calorimeter on the upper side. The average hot temperature was 2282 deg. fahr. (1250 deg. cent.), and the cool side for the rates of flow resulting about 850 deg. cent. Tested standard refractory bricks and special materials. No attempt seems to have been made to obtain temperature coefficients. The values found for the standard refractories are lower than those given by most other investigators.

R-17—Hartman, M. L., Westmont, O. B. (Carborundum Co., Niagara Falls, N. Y.), Physical Characteristics of Specialized Refractories. *Jl. Am. Electrochem. Soc.*, Oct., 1924 and *Jl. Am. Ceramic Soc.*, Feb., 1925.

Followed Dudley's method (R-11) using a well-insulated special furnace with a 22-in. sq. test area. The furnace was filled with checkerwork and heated with oil fuel. Measured flow with a guard-ring water calorimeter, 8 in. sq. for center, and two guard rings making 18 in. square. Used maximum temperatures of 2730 deg. fahr. (1500 deg. cent.). Three holes drilled to $^1/_4$ in. of the hot surface were used to measure temperatures through the wall, the thermocouples being slid to any required distance. The main work was with carborundum, but fireclay was used as a backing on the cooler side. The conductivity at the various temperatures was apparently determined by the slope of the temperature curves, and the known heat flow.

The most interesting feature of their conclusions is that the conductivity (at a given temperature) increases with the rate of heat flow. The increase found varies for different materials but is large. No explanation is offered except that it might be caused by the radiation factor across the pore spaces. Such a relationship would be of great import in heat-transmission problems, and it might explain the different results found by different investigators. A possible cause for the apparent change might be in- or ex-filtration under different heating conditions, which would be more liable to occur with thin test specimens. It would seem probable, however, that the variations found in this investigation are due to errors in temperature measurement.

R-18—Howe, R. M., and Phelps, S. M. (Mellon Institute, Pittsburgh, Pa.), Heat Transmission with Special Reference to the Stoker Fired Boiler. *Jl. Am. Ceramic Soc.*, vol. 5 (1922), pp. 420–429.

The object of the tests was to show that air or gases pass through the refractory and affect the wall temperatures through it, but the rate of flow was not measured. Negative or positive pressures were carried in at small furnace and temperatures taken at various depths on the wall. The order of the values agrees with those which would be expected from the passage of the hot gas or cool air.

R-19—Schack, Alfred. Heat Transfer in Furnaces as Caused by Radiation of Gases. *Berichte der Fachausshüsse des Vereins deutsches Eisenhüttenleute*, Bulletin no. 55, Dec., 1923. Abstracted in *Fuels and Furnaces*, vol. 2 (July, 1924), no. 7, pp. 675–678.

Develops formulas for the transference by radiation in furnaces with hot gases of varying composition. The gases are assumed free of solid particles. The paper is an excellent example in the reduction of complicated formulas to a form available for the use of engineers. There would seem to be doubt on the correctness of the basic assumptions made, and a need of distinguishing between flame radiation and that of gases in which combustion is completed.

Some Results of Condenser Operation

By EDWIN B. RICKETTS,[1] NEW YORK, N. Y.

THERE are many references in engineering literature to the results of condenser tests. The results given, however, are usually those obtained on acceptance tests where the conditions under which the apparatus operated were favorable to high efficiency. While the results of such tests are of interest as showing the ultimate goal of condenser operation, power-plant operators are mainly interested in the performance of condensing apparatus under commercial operating conditions.

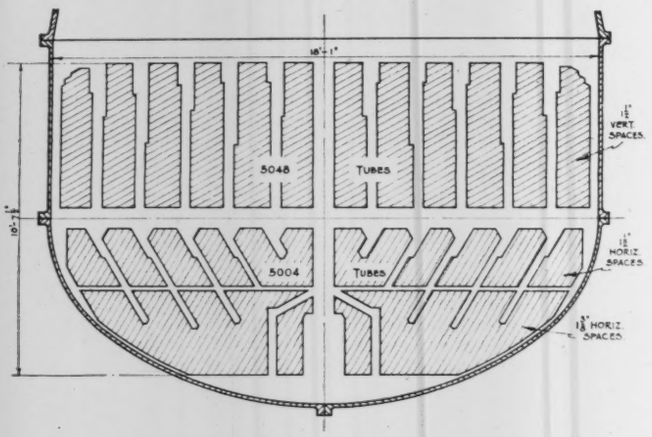

FIG. 1 CONDENSER "A"

(Two-pass; 10,052 1-in. O.D. No. 18 gage tubes, 19 ft. net length; surface, 50,000 sq. ft. approx.)

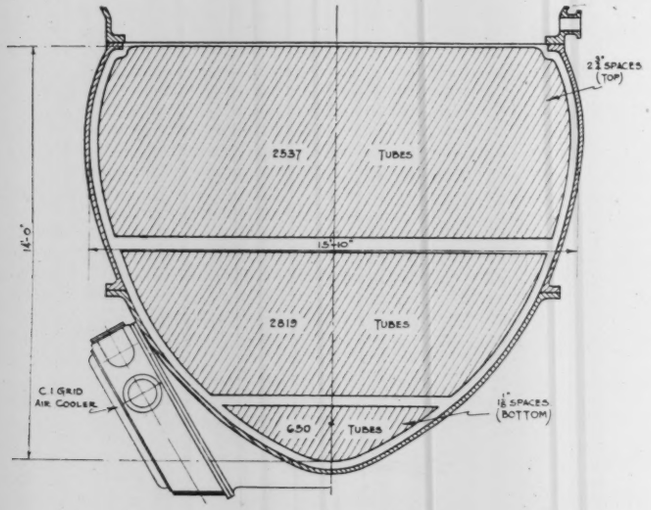

FIG. 2 CONDENSER "B"

(Single-pass, divided water box; 6006 ⅞-in. O.D. No. 18 gage tubes, 21 ft. 9 in. net length; surface, 30,000 sq. ft. approx.)

In the table and curves herewith submitted are given the results of a year's operation of the four condensers illustrated in Figs. 1 to 4. These four condensers differing radically in design were operated under the same water conditions and under the same supervision. The data given are based on about fifty tests made at approximately weekly intervals during twelve consecutive months in 1925 and 1926. These tests were made by the station test crew for the purpose of aiding in the operation of the apparatus under consideration; calibrated instruments were used, and the usual precautions for accuracy taken.

The data presented are probably not sufficiently comprehensive to warrant definite conclusions as to the relative excellence of the designs tested; it is believed, however, that they will provide condenser designers and operators with food for thought.

TABLE 1 RESULTS OF A YEAR'S OPERATION OF FOUR CONDENSERS DIFFERING RADICALLY IN DESIGN

	Type of Condenser A		B		C		D	
1925	Average heat transfer, B.t.u.	Average vacuum, in. Hg	Average heat transfer, B.t.u.	Average vacuum, in. Hg	Average heat transfer, B.t.u.	Average vacuum, in. Hg	Average heat transfer, B.t.u.	Average vacuum, in. Hg
August	310	28.24	496	28.23	376	28.41	477	28.34
September	328	28.35	588	28.46	476	28.30	667	28.37
October	245	28.65	457	28.76	447	28.73	438	28.72
November	238	28.91	365	28.81	390	28.89	459	29.14
December	220	29.03	307	28.81	324	28.94	277	28.99
1926								
January	212	29.18	370	29.27	356	29.18	306	29.29
February	212	29.30	355	29.31	295	29.09	417	29.35
March	208	29.13	367	29.20	339	29.12	343	29.18
April	258	29.12	413	29.13	390	29.08	314	29.14
May	268	28.93	422	28.83	349	28.69	354	28.88
June	319	28.74	514	28.74	522	28.73	411	28.64
July	283	28.43	531	28.49	438	28.31	411	28.36
Average	258	28.83	432	28.83	392	28.78	406	28.87
Total hours run		7688.5		6295.25		7073	5318	
Year installed		1919		1924		1924	1914	
Tubes renewed		2848		0		291	506	
Times sandblasted		0		3		3	1	
Times washed		13		15		13	1	

NOTE: All transfer rates based on arithmetical mean temperature difference.

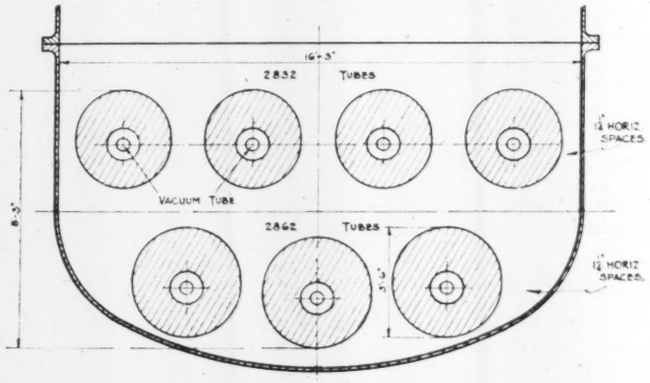

FIG. 3 CONDENSER "C"

(Single-pass, divided water box; 5694 ⅞-in. O.D. No. 18 gage tubes, 23 ft. net length; surface, 30,000 sq. ft. approx.)

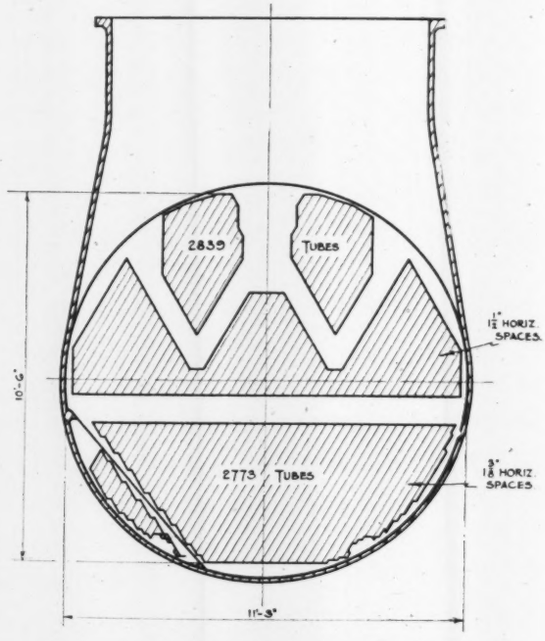

FIG. 4 CONDENSER "D"

(Two-pass; 5612 1-in. O.D. No. 18 gage tubes, 17 ft. net length; surface, 25,000 sq. ft. approx.)

[1] Research Engineer, New York Edison Co. Mem. A.S.M.E.

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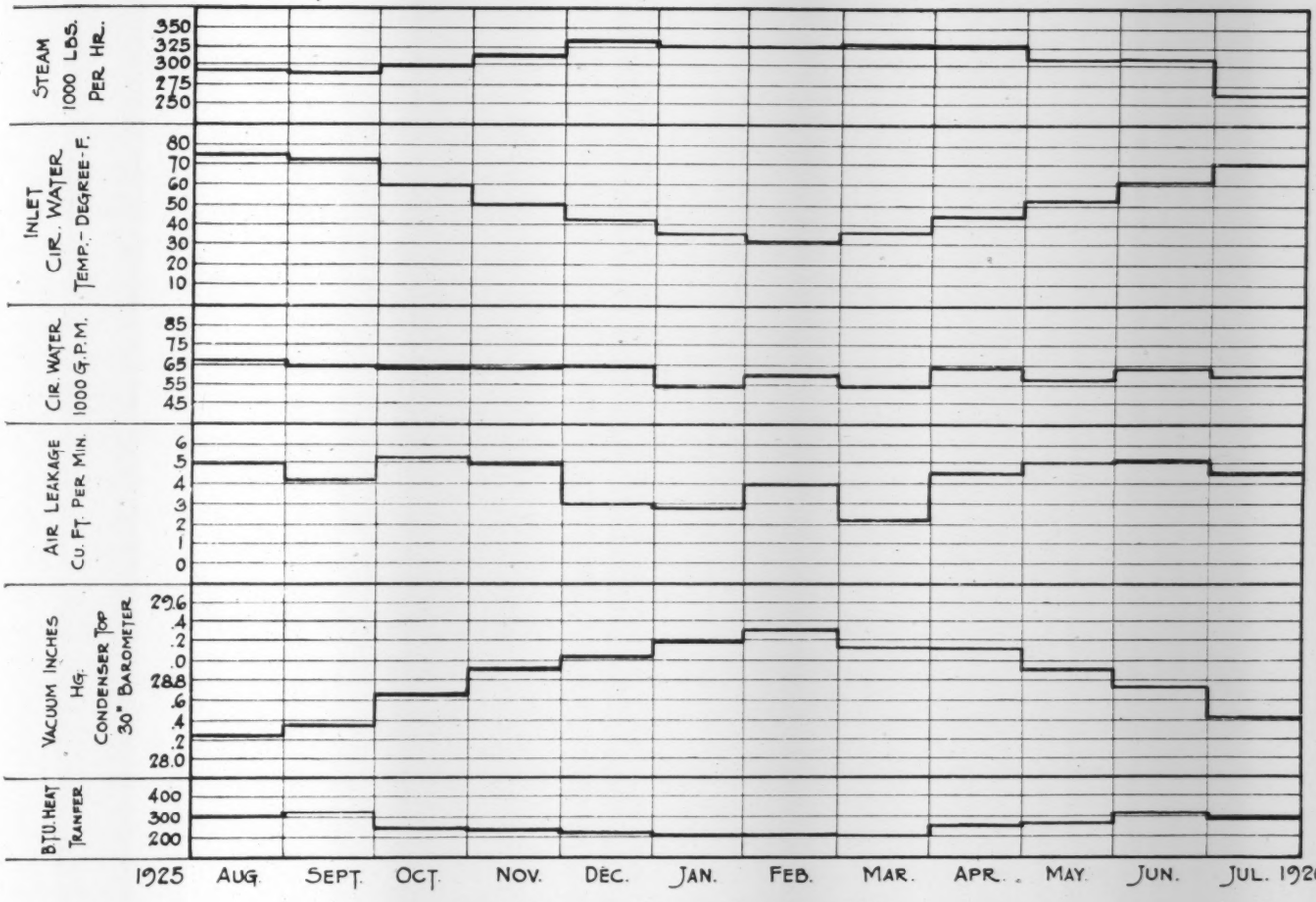

FIG. 5 OPERATING RESULTS, CONDENSER "A"

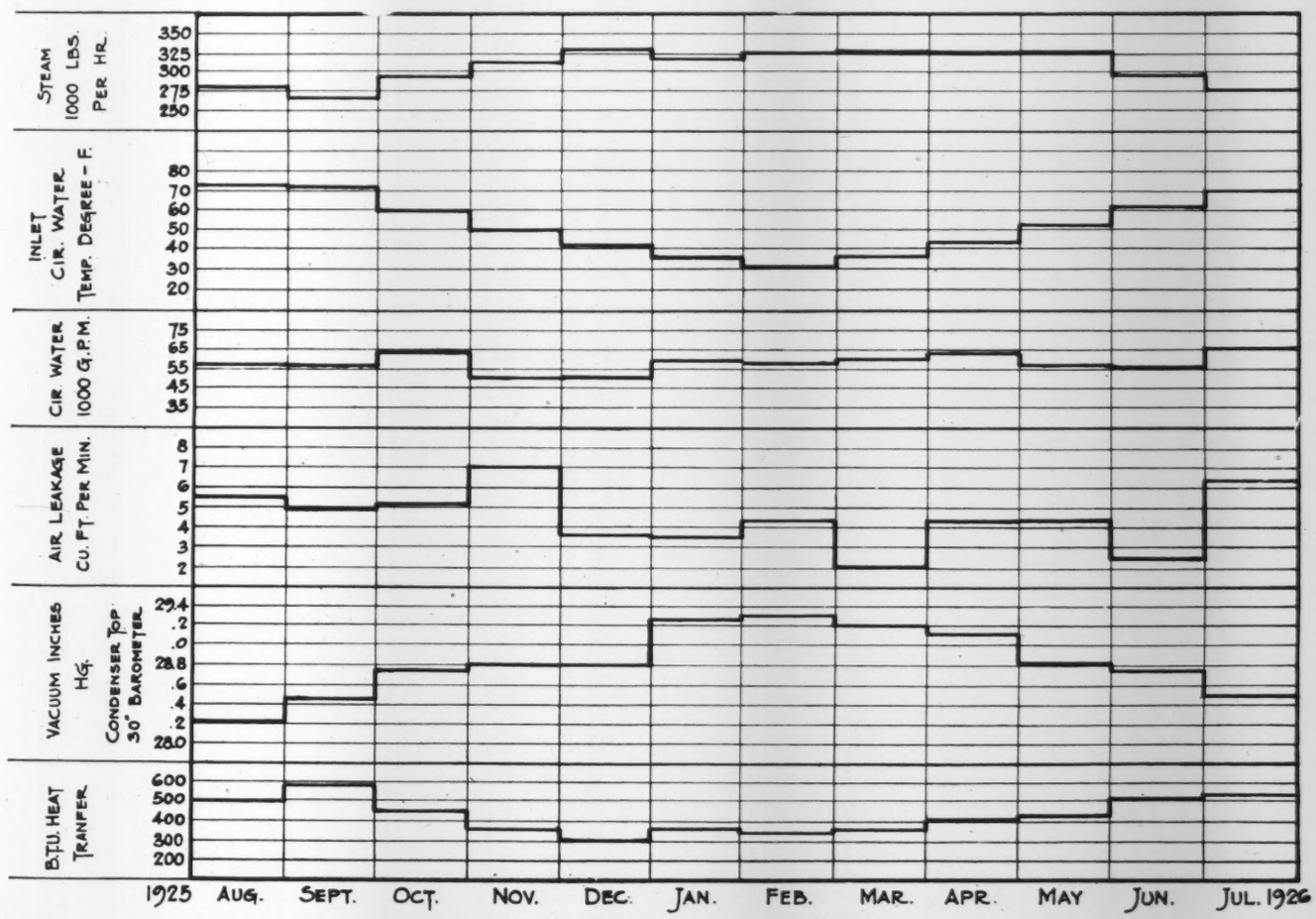

FIG. 6 OPERATING RESULTS, CONDENSER "B"

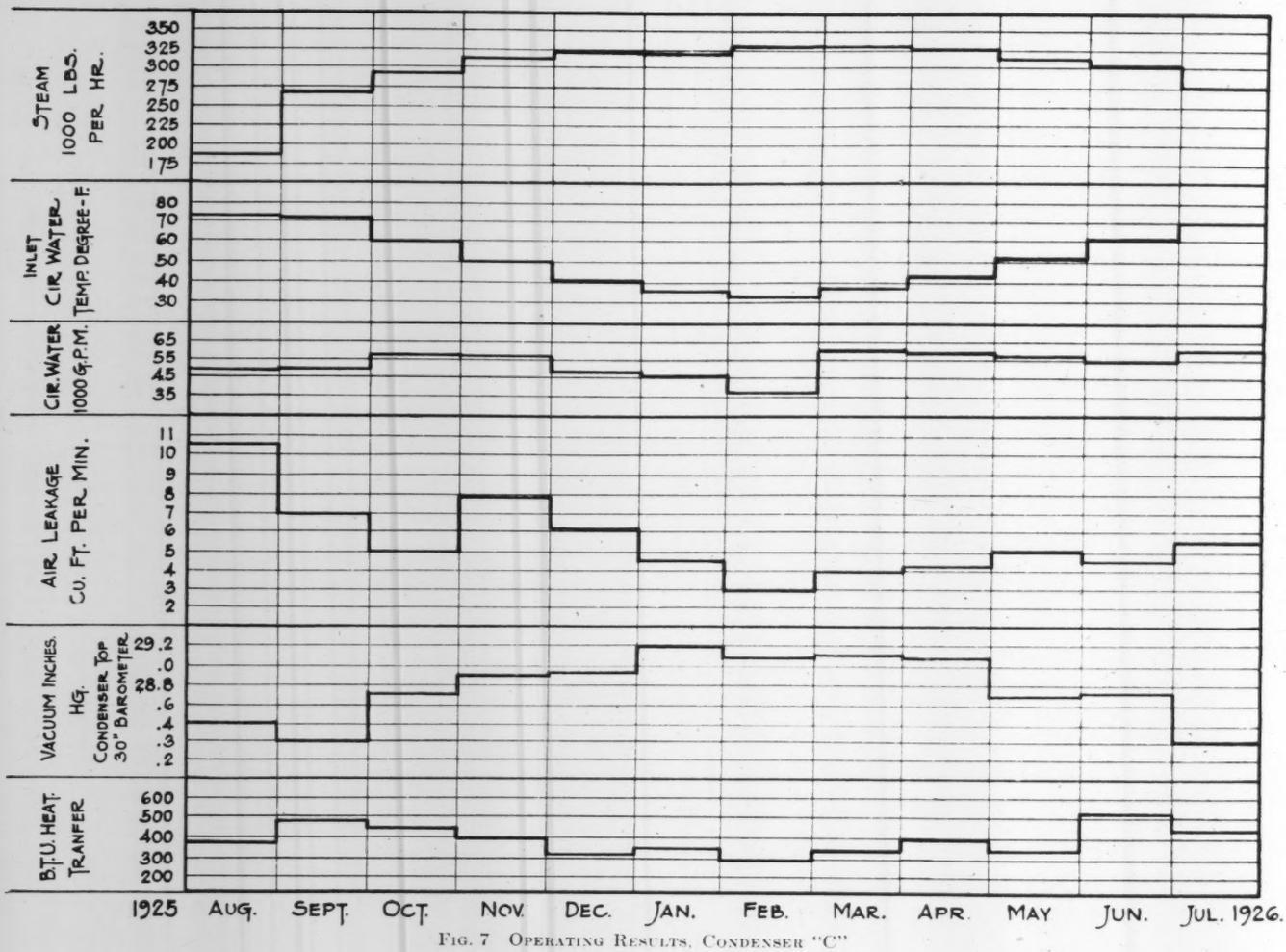

FIG. 7 OPERATING RESULTS, CONDENSER "C"

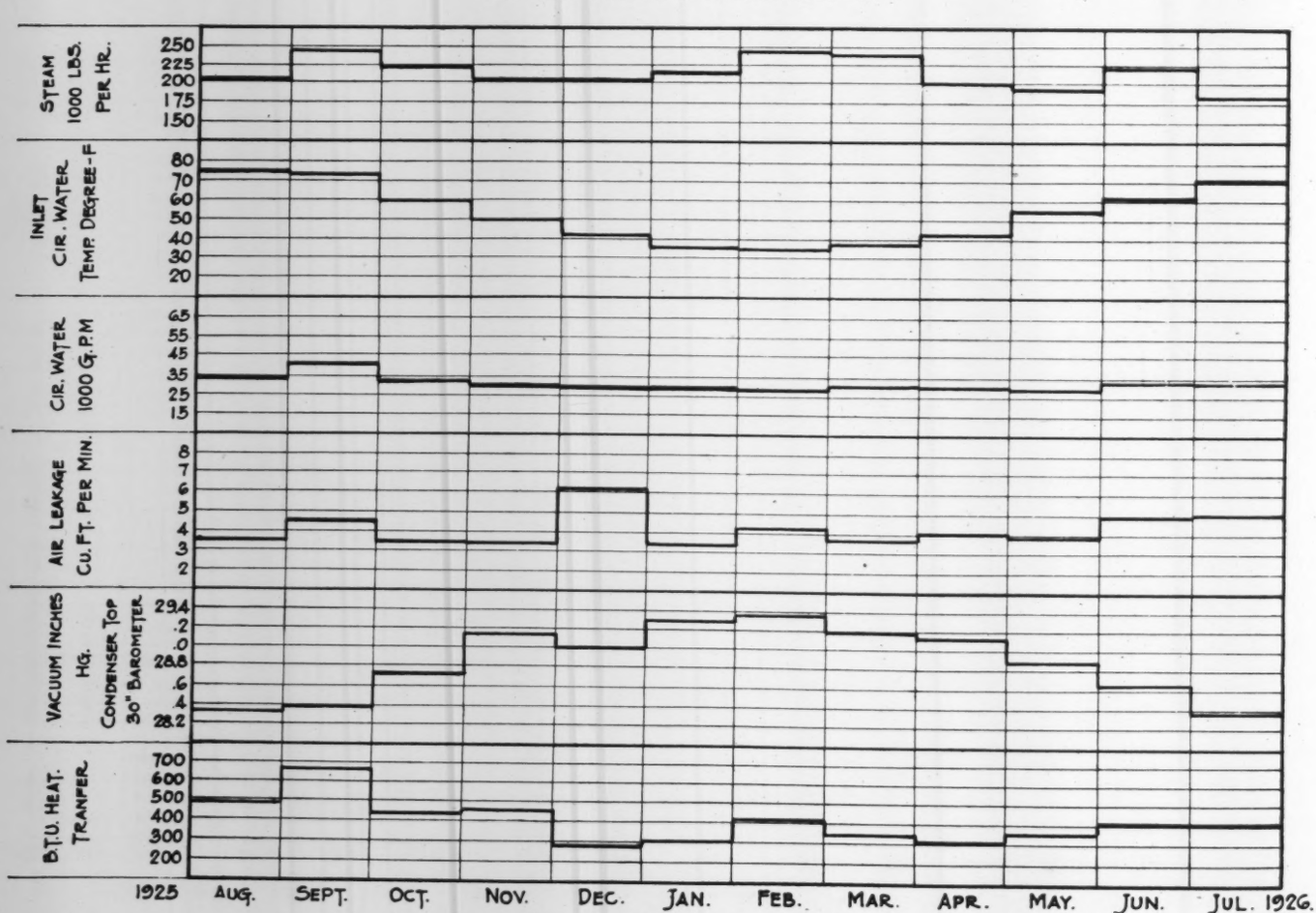

FIG. 8 OPERATING RESULTS, CONDENSER "D"

The Modern Oil Engine

A Review of the Means Used by Foreign and Domestic Oil-Engine Builders to Fit This Prime Mover to the Constantly Broadening Field of Its Application

By EDWARD C. MAGDEBURGER,[1] WASHINGTON, D. C.

DESPITE the existence of a large number of highly instructive technical papers dealing with various phases in the progress of the oil engine toward its ultimate place in modern life, and probably for that very reason, a brief review of the efforts of the small army of engineers engaged in oil-engine building would be of interest to fellow engineers pushing other wheels of civilization. The ability of the Diesel type of oil-engine to burn low grades of oil, and with great efficiency, has been so thoroughly advertised that an immediate demand exists for oil engines suitable for propulsion of warships, aircraft, locomotives, trucks, and automobiles. The failure of the existing commercial types to qualify for these services is largely due to their inability to meet weight and space requirements, although engines ranging in size from 1 hp. to 2000 hp. per cylinder have already been constructed and tested. A unit of 15,000 hp. in nine cylinders has been installed and put into operation.

An oil-engine unit consists essentially of a combustion chamber where the chemical energy of the fuel is converted into the mechanical energy of the moving piston, and the structure necessary to contain this chamber and transmit the power developed to the rotating shaft. Therefore efforts to reduce the specific weight of the oil engine have been directed along two distinct lines: reducing the weight of the structure for a given effective cylinder content, and improving the capacity of a given cylinder volume to develop more power.

Specific cylinder volume, or volume swept by the piston, necessary to develop one brake horsepower per minute is the measure of the latter, whereas the engine weight per brake horsepower indicates the combined effect of both.

Both of these lines of attack should not of course imperil the safe and reliable operation of the engine. Herein lies the first fundamental division of engineering opinion. Some see in the two-stroke cycle, giving roughly twice the horsepower out of the same cylinder contents, a feature worth developing. Others assert that the established and unquestioned reliability of the four-stroke cycle must be maintained, and other means found to offset the disadvantage of its requiring twice the time for the same amount of work developed. Much heated debate resulted in the past over this point and it is not the intention of the author to champion the cause of either side but rather to attempt to record the actual efforts put forth by both to prove their point.

I—FOUR-CYCLE ENGINES

Oil engines of the four-cycle type, being historically the first to be developed commercially, have attained a very high degree of reliability, and show only minor variations in the design of the vital parts. Much operating experience has been gained in various fields of application extending over long periods of time, and with widely different types, and the line of progress is very much easier to determine.

One of the greatest hopes for development of the four-cycle engine lies in the adoption of higher shaft and piston speeds, largely brought about by the splendid performance of the German submarine engines during the late war. The largest of these engines, which has, with minor modifications and slight reduction in rating, been adopted as a part of the propelling plant of some of the new U. S. submarines (Fig. 1), stands out as the utmost dared in this direction by the designer (No. 1, Table 1). The war was over before any service experience was obtained with these engines, and, although a number of them have since been installed in merchant ships,[2] their rating has been considerably reduced, as shown by the lower figures in Table 1.

Higher Speeds to Reduce Weight and Space Requirements

However, as the result of this daring, the well-known Burmeister and Wain Company built its double-acting experimental cylinder, which has been since incorporated in a number of large engines in apparently successful operation on the high seas. The high piston speed of this engine (No. 2, Table 1), if justified by service experience,[3] is a considerable advance over the prevailing practice of the same builder, and contributed considerably to the reduction in weight shown as compared with single-acting engines built by its American licensees—Cramps—(No. 3, Table 1). It is true that another factor, namely, introduction of the double-acting principle and the omission of the injection-air compressor (both of which will be discussed later) contributed largely to the result, but the fact that, the specific weight has been reduced by (1238—867)/1238 = 30 per cent due to speed increase alone, can hardly be denied.

A notable example, where the designer achieved considerable advance in the direction of weight and space reduction by relying only on the use of high relative speed, is the Maybach[4] engine (Fig. 3), said to be rather extensively used in Germany in rail cars and small marine applications (No. 4, Table 1). Here also the orthodox air injection of fuel has been retained, although the modern tendency is to begin lightening up the engine with the elimination of the injection-air compressor.

Intermediate Transmissions. The question arises, naturally, what is it that stands in the way of progress, by increasing both the piston and rotative speeds. There are two types of difficulties encountered: one set of troubles that will have to be overcome is mechanical, the other thermodynamical. To the mechanical group belong the necessity of using intermediate transmissions, such as gear drives,[4,5] electric transmission,[6] and hydraulic type of gear,[7] all of which introduce additional weight to offset the gain from the high speed of the oil engine itself, and additional complication of installation, which may be quite considerable and may add a questionable reliability factor of the transmission itself. Proponents of these drives,[8] possessing quite naturally a better knowledge of the devices, do not admit the existence of any such questionable features, and the service experience gained with the pioneer installations apparently vindicates their convictions since new installations of either of the three indirect drives for ships and locomotives are being made extensively.

Destructive Critical Speeds. Another bugaboo of the mechanical group that is being rapidly put under control is the destructive critical speeds resulting from synchronous torsional vibration. It is when the high-speed oil engine for submarine service came into existence that these were encountered, and to the "dreadful" submarine must go the credit for eliminating torsional vibration

[1] Aide on Diesel Engines, Bureau of Engineering, Navy Department.

[2] Munsterland, Havelland, and Vogtland. See *The Motorship* (British), Oct., 1923, p. 225; and *Motorship* (N. Y.), May, 1923, p. 335.

Contributed by the Oil and Gas Power Division for presentation at the Annual Meeting, New York, December 6 to 9, 1926, of the American Society of Mechanical Engineers. All papers are subject to revision.

[3] M. S. Gripsholm. See *Motorship* (N. Y.), Dec., 1925; Mechanical Engineering, Jan., 1926, p. 81. It is hoped that engines built by the British licensee of Burmeister & Wain Co., of exactly the same cylinder dimensions but running at 115 r.p.m. (M. S. *Asturias*—see No. 16, Table 1) and 96 r.p.m. (M. S. Carnarvon Castle, *The Motorship* (British), July, 1926, p. 120), do not reflect service experience with the high piston speed of engines in the M. S. Gripsholm.

[4] *Oil Engine Power*, Nov., 1924, p. 595; Dec., 1924, p. 658.

[5] A considerable number of gear-drive installations for tugs have been made in this country. See *Motorship* (N. Y.), Nov., 1925, p. 826; Aug., 1926, p. 590; July, 1926, p. 521, but the U. S. Shipping Board refused to recognize this solution for ship propulsion, although it was the cheapest offered.

[6] Electric drive has recently been successfully applied in considerable number to tugboats (See *Motorship* (N. Y.), Feb., 1925, p. 115, tow boats; July, 1925, p. 505, ferries; Aug., 1926, p. 599, Sept., 1926, p. 674, tankers; and May, 1926, p. 352, locomotives.

[7] Vulcan Hydraulic Gear for Ships, *Motorship* (N. Y.), Jan., 1925, p. 28.

[8] Dr. Frahm, of Blohm-Voss Co., has contributed a most interesting paper comparing weight and space requirements of high-speed geared installations for ship propulsion. See *Motorship* (N. Y.), Feb., 1925, p. 103.

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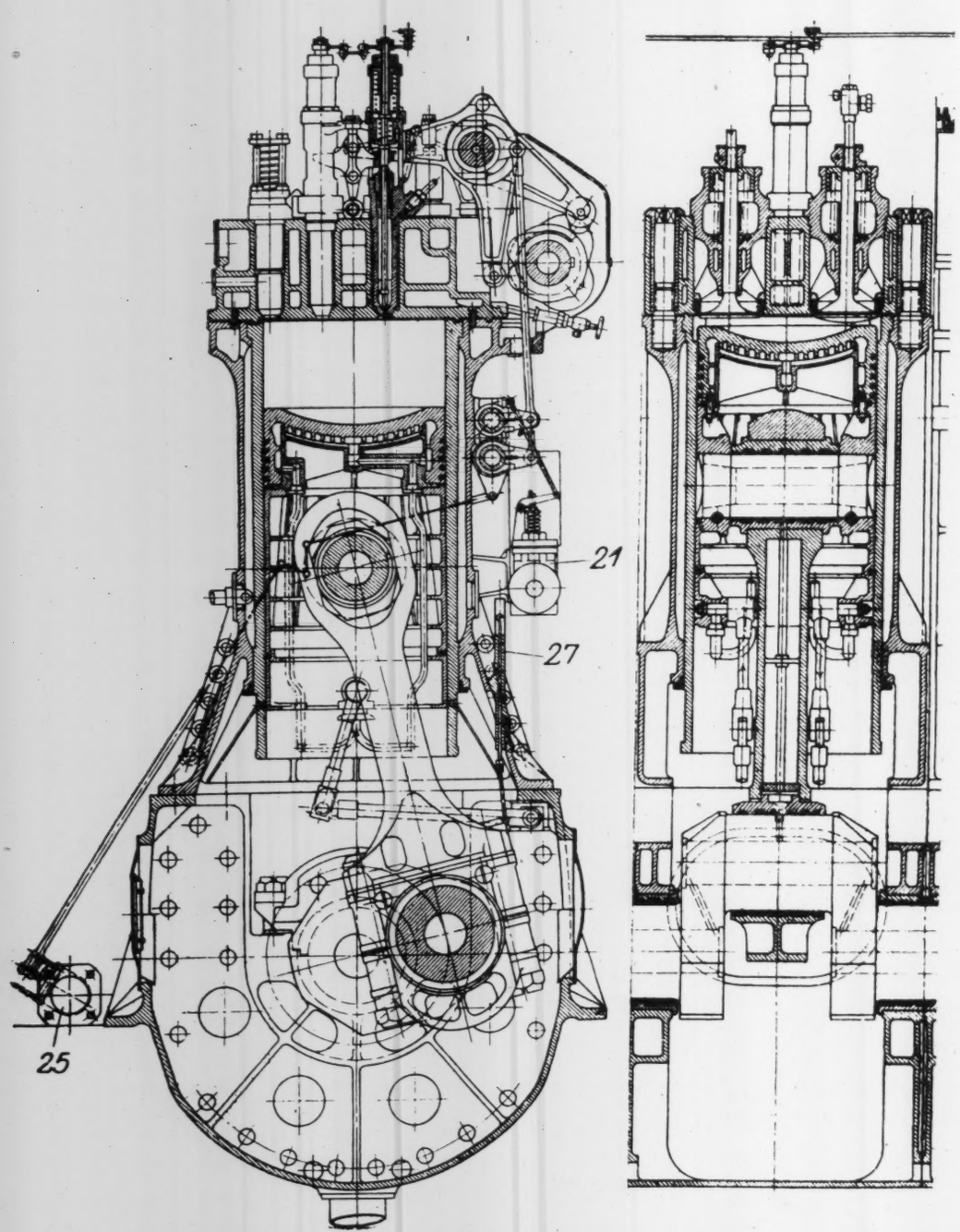

Fig. 1 Sections Through Cylinder of the 3000-B.Hp. German Submarine Engine (M.A.N.)

from the path of oil-engine progress. With the increase in engine speed also increases the number of torque impulses conveyed to the shaft, and since a given shaft system has a constant frequency of free or natural vibration, the periods of synchronism descend into the operating range and may subject the shafting to excessive stresses resulting in failure. This trouble, however, has been largely eliminated, and although improvement in the methods used is still desirable, no destructive critical torsional speeds need exist through the operating range, unless the required range is excessively large as in propelling plants of submarines, or other warships for that matter, where such a long engine operating range, as in one instance from 75 to 450 r.p.m., is very desirable, and where it must be unavoidably somewhat restricted.

Increased Heat Stresses. Another type of trouble that had to be conquered was the increased heat stresses resulting from increase in engine speed. These are confined mostly to piston crown and cylinder head, and with the existence of the two idle strokes of the four-stroke cycle do not reach excessive limits and become of importance only after the cylinder bore exceeds 10–12 in. in diameter. At any rate, provision for free expansion of both piston and cylinder head in the B. & W. design (Fig. 2), or the use of high velocity of cooling medium in the M.A.N. design (Fig. 1) of cylinder head and piston, solves the problem.

Another part that is exposed to the increased heat stresses is the exhaust valve. Here the new heat-resisting alloy steels solve the problem for smaller sizes in the same way as they did for the high-speed automobile and aircraft motors. Internal cooling of the valve seat and stem used on very large engines adds but very little to the unavoidable complication of the water-cooled valve cage. The cylinder-head design introduced by Tosi (Fig. 4) provides a different and very attractive solution of the heat problem by using smaller valves in the head, permitting better cooling of the head, but using

TABLE 1 DATA ON FOUR-CYCLE ENGINES[1]

No.	Type of engine	S.A. or D.A.	No. of cylinders	B.Hp. Total	B.Hp. One cylinder	Bore, in.	Stroke, in.	R.p.m.	Piston speed, ft. per min.	Brake M.E.P. lb. per sq. in.	Specific volume, cu. ft. per hp-min.	Weight, lb. Total	Weight, lb. Per b.hp.	Remarks
1	German Submarine	S.A.	10	3000	300	20.86	20.86	390	1356	85.4	5.35	207,000	69.0	Submarine rating
				1650	165	20.86	20.86	230	800	79.6	5.74	207,000	125.0	Motorship rating
2	Burmeister & Wain	D.A.	6	6750	1125	33.07	59.05	125	1238	73.5	6.23	1,130,000	168.0	Without air compressor
3	Cramps-B. & W.	S.A.	6	1700	283	29.13	45.28	115	867	64.8	7.09	600,000	352.0	
4	Maybach	S.A.	6	140	23	...	...	1300	...	...	...	2650	18.9	
5	Nobel (1908)	S.A.	8	200	25	7.87	8.65	600	865	78.4	5.84	4400	22.0	V-type
6	McIntosh & Seymour	S.A.	12	1000	83	14.0	18.0	325	975	73.3	6.25	80,000	80.0	V-type
7	Hamburg-Mannheim	S.A.	6	1600	267	27.16	39.37	120	787	77.5	5.92	385,000	240.0	
8	N.-E. Werkspoor	D.A.	6	4000	667	32.28	59.05	95	935	60.6	7.56	1,165,000	291.0	
9	Pacific-Werkspoor	S.A.	8	2900	363	31.5	51.18	95	810	76.0	6.04	1,100,000	380.0	
10	McIntosh & Seymour	D.A.	4	2700	675	32.0	52.0	95	823	70.9	6.46	760,000	281.5	
11	McIntosh & Seymour	S.A.	6	2700	450	32.0	60.00	95	950	77.8	5.9	800,000	296.0	
12	Beardmore-Tosi	D.A.	3	800	267	20.0	24.5	240	980	60.3	7.61	157,000	196.0	
13	Beardmore-High Speed	S.A.	8	400	50	8.25	12.0	750	1500	82.3	5.56	4500	11.25	
14	Blohm & Voss-M.A.N.	S.A.	6	1750	292	23.62	27.56	215	988	89.1	5.15	363,000	209.0	Supercharged
15	Italian-B. & W.	D.A.	8	10,000	1250	33.07	59.05	125	1238	81.7	5.6	1,900,000	190.0	Supercharged without air compressor
16	Harland & Wolff-B. & W.	D.A.	8	7500	938	33.07	59.05	115	1131	67.2	6.82	.....	...	With air compressor

[1] Ten per cent allowance made for piston-rod area.

them both for inlet and exhaust, so that the incoming induction air serves to remove the heat absorbed by the valves from the hot exhaust during the immediately preceding exhaust stroke. Such double-duty valves have been adopted also in the new design of Werkspoor double-acting engine (Fig. 7).

Besides the increase in speed, modifications in the orthodox means (requiring a crank mechanism for each cylinder) to transmit the power developed to the shaft have been studied, with the result that several solutions have passed the inevitable criticism following the attack of anything as established as was the single-acting four-cycle type. Many more have been proposed from time to time, but the courage of their sponsors has so far not been sufficient to overcome the obstacles on their way to adoption by oil-engine builders.

V-Type Construction. As early as 1908, when Nobel, the oil magnate of Russia, desired a propelling plant for his yacht, the weight and space requirements could not be met by the four-cycle engine of the day in any other way except by resorting to special materials and adopting a so-called V-type of construction (No. 5, Table 1),[9] so that two cylinders alternately transmit their torque to the same crankpin. Since then a large number of moderate-size engines of this type have been built in Sweden by the Atlas Diesel Aktiebolaget (Polar type) and are offered by their American licensee, the McIntosh & Seymour Corporation for installation in railroad cars.[10] The latest development of this type of engine is shown in Fig. 5 (No. 6, Table 1). Such an arrangement produces undoubtedly a more light and compact engine but due to the increase in overall width is unsuitable for many applications.

Common Crank Mechanism. A further step in this direction is the use of a common crank mechanism by two adjoining four-cycle cylinders alternately, as adapted to a large-size engine by the Hamburg-Mannheim Co., Ltd. (Fig. 6), the first engine of this type having been recently installed in a motorship.

Here again the reliability of the standard air-injection type of single-acting four-cycle engine has not been impaired and the advantages of light weight and compact construction result exclusively from the arrangement adopted which lends itself admirably to accommodating the air-compressor drive from the same rocker arm that serves the pair of working cylinders. Many additional advantages are claimed for this arrangement such as, for instance, that it is equivalent to a crosshead design though much shorter in height, etc.; but time alone will tell whether it has no serious disadvantages of its own.

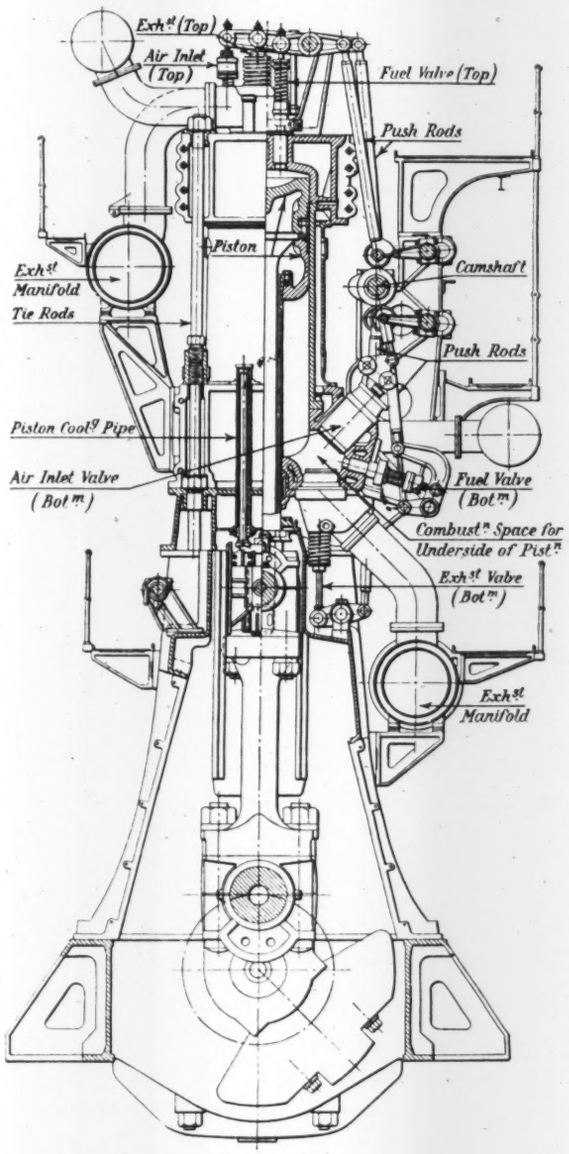

FIG. 2 CYLINDER SECTION OF BURMEISTER & WAIN DOUBLE-ACTING ENGINE

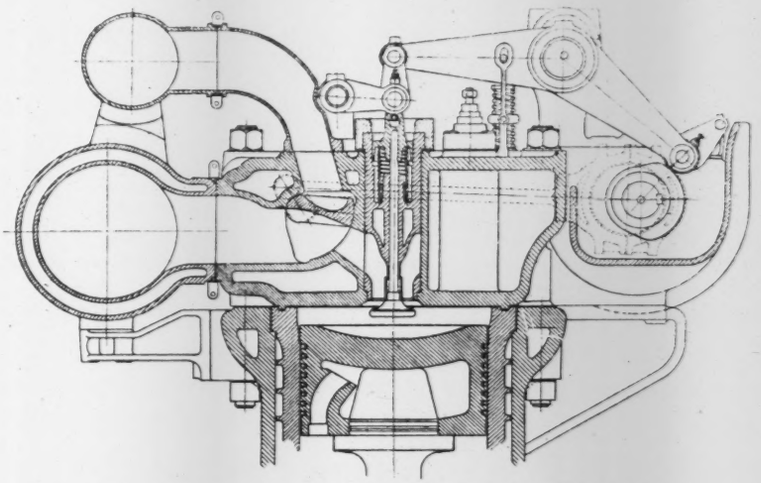

FIG. 4 SECTION THROUGH TOSI TYPE OF CYLINDER HEAD

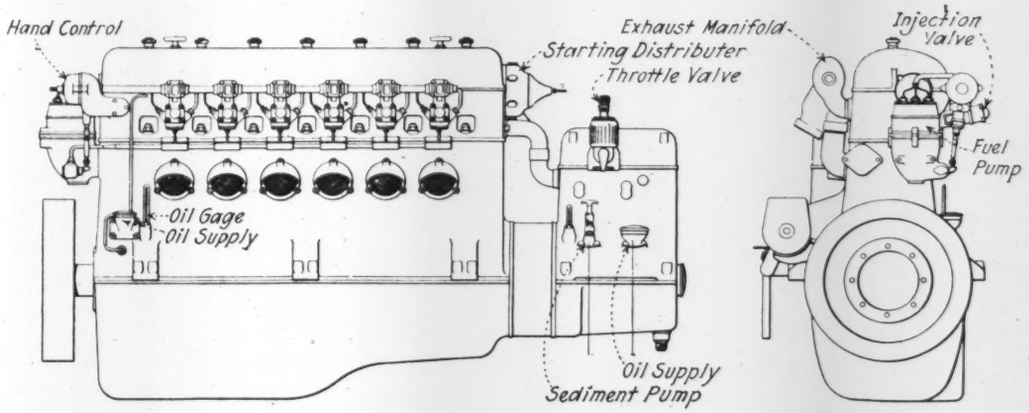

FIG. 3 MAYBACH OIL ENGINE

The Double-Acting Principle. Among the recent arrivals into the oil-engine industry is the application of the double-acting principle. This statement needs probably to be modified slightly since four-cycle double-acting oil engines of the horizontal tandem type were built by the M.A.N. Company years ago in considerable numbers. Reference is made here to the recent efforts of applying this principle to vertical engines, suitable for ship propulsion. As

[9] Trans. Inst. Eng. and Shipbuilders in Scotland, Apr., 1926, p. 566.

[10] *Oil Engine Power*, Nov., 1923, p. 529.

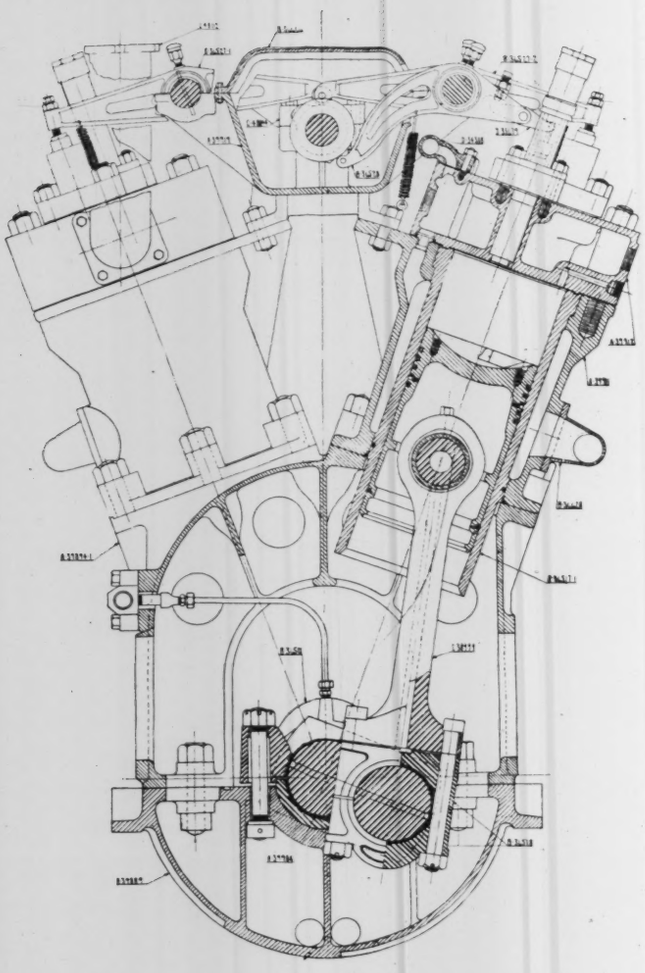

FIG. 5 SECTION THROUGH MCINTOSH & SEYMOUR LOCOMOTIVE ENGINE (1000 B.HP.)

many as four different experimental cylinders of the four-cycle double-acting type have been built. Engines of two of these types have already been installed in substantial numbers for ship propulsion. The previously referred to B. & W. type[3] (No. 2, Table 1), leads historically and in size of cylinder developed. The North Eastern-Werkspoor type[11] does not include the advantage of higher piston speed, and in fact the lower side of the piston has a considerably lower compression pressure and works on a modified cycle (Figs. 7 and 8). Numbers 8 and 9, Table 1, afford a ready comparison of the single- and double-acting engines of this type of nearly the same cylinder dimension.

The results obtained from a double-acting experimental cylinder said to have been built by the Atlas Diesel A.-B. (Polar type) in Sweden just prior to the late war, were, due to the war, neither published nor utilized until the McIntosh & Seymour Corporation contracted to build one engine of this type for the Shipping Board program, in addition to three of the single-acting type (Nos. 10 and 11, Table 1). A section of this engine is shown in Fig. 9.

Several well-known European builders of four-cycle oil engines have combined their talent and resources and built a high-speed double-acting marine oil engine of the Beardmore-Tosi type, which drives the ship's propeller through a Vulcan hydraulic gear. The results of this installation[12] will be watched with great interest by all engineers, since it is quite possible that this may be the progenitor of one of the oil-engine types of the future. (See No. 12, Table 1.)

Whatever else extended service experience may prove or disprove, the results to date indicate conclusively that there is more than one way to design a successful four-cycle combustion chamber for the lower cylinder half, and the much-discussed and feared stuffing box for the piston rod is no problem at all. Much credit is due to the Burmeister & Wain Company for their ingenious design of the piston rod[3] that made it possible to design a combustion chamber using the standard Diesel cycle, and to the Werkspoor Company for their more conservative and cautious solution[9] of the lower cylinder problem, employing lower compression.

Elimination of the Injection-Air Compressor. Probably the most natural step in weight reduction at first thought would be the elimination of the injection-air compressor with its air coolers and considerable amount of high-pressure piping, including an air receiver or air bottle of substantial weight. This of course provided that the same indicated mean effective pressure could be realized by some system of airless injection of fuel. Then not only reduction of the total weight of the engine but also improvement in the specific cylinder volume required to realize one brake horsepower could be obtained. The air injected with the fuel is really such an ideal medium to separate the fuel charge into small particles and to accelerate and carry these oil particles to all parts of the combustion chamber, exposing a tremendous surface of the fuel charge to absorb the heat of the compressed-air charge in the cylinder, and using this heat to further atomize the fuel particles until they all can find sufficient oxygen to burn completely and without producing smoke. Small wonder, then, that the first substitutes for air injection found but little appreciation of their rather mediocre performance, and even today, after much time and effort has been spent in developing various types of airless injection, a large percentage of the oil-engine builders prefer the assured reliability of air injection.

Space does not permit going into the details of this long chapter of oil engine development, and the reader is referred to the volum-

[11] *Motorship* (N. Y.), Feb. and July, 1926, pp. 124 and 526; *The Motorship* (British), June and Oct., 1926, pp. 84 and 241.

[12] *Motorship* (N. Y.), May, 1925, p. 370.

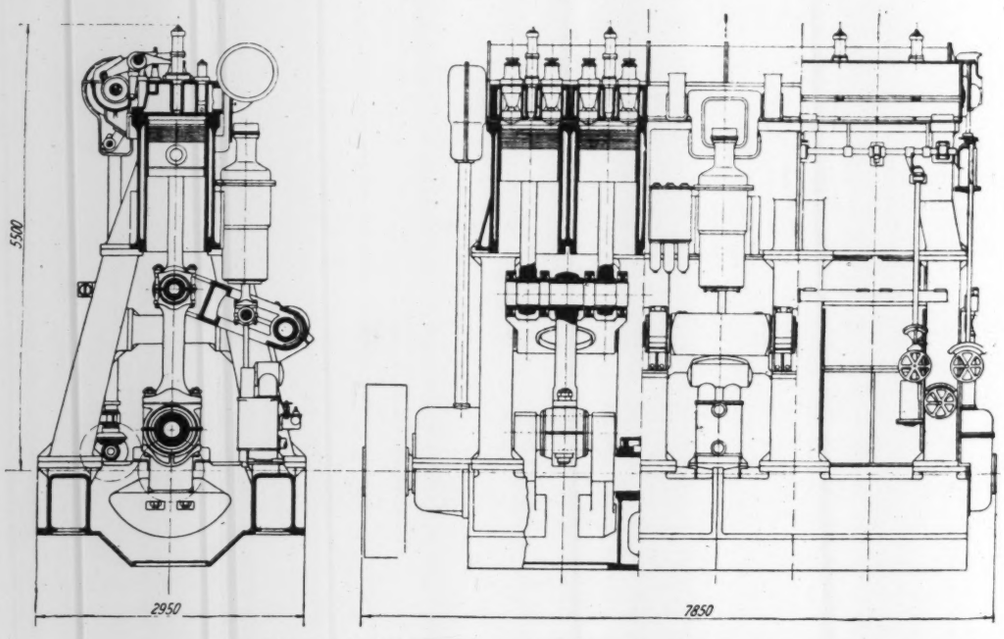

FIG. 6 1600-B.HP. HAMBURG-MANNHEIM ENGINE

minous current literature covering it;[13] suffice it here to say that three different types of airless injection of fuel have been developed that, judging by the fact that they have been adopted by an increasing number of eminent builders of four-cycle engines, bid fair to make the injection-air compressor survive only in the memories of the pioneers.

Mechanical Injection employing pump pressures ranging from 2000 to 20,000 lb. per sq. in., following the pioneer work of McKechnie of Vickers, Ltd., has been adopted by Hesselman (Polar) in Sweden, M.A.N. and Deutz in Germany, and a number of Pacific Coast oil-engine builders and the Foos Company in this country, as well as by American licensees of the above European firms. The Beardmore Company used it in their high-speed engine[14] (Fig. 10) that made the now famous cross-country run in a Canadian rail car (No. 13, Table 1). Minor modifications embodying the individual preferences of designer in an effort to overcome the originally encountered smoking due to the dripping of fuel and its incomplete combustion, mark the greater number of existing solutions, but all rely essentially upon high pressure on the fuel to bring the fuel charge into sufficiently intimate contact with the body of combustion air to result in complete combustion. The low fuel consumption at all loads and the fine regulation even at no load are the outstanding advantages, in addition to weight reduction resulting from the elimination of air injection and the attached air compressor.

Injection Chamber. Another solution of airless injection is the so-called injection chamber (Fig. 11), a type developed out of the original efforts of Brons in Holland to substitute inert products of the combustion chamber for injection air as the carrier and atomizer of the fuel charge. A number of different designs of injection chamber where a small part of the fuel charge is burnt or exploded and carries the rest of the charge into the cylinder proper to be distributed, atomized, and burnt, have been perfected and applied to four-cycle engines ranging in size from small farm engines to 250 b.hp. per cylinder in a Körting engine. The extremely simple fuel pump necessary and fuel consumption comparing favorably with that of air-injection and mechanical-injection engines make this method a very promising solution of the high-speed, light-weight engine.

A purely American solution of the air-compressor problem is credited to W. R. Price,[15] who caused the combustion air in the cylinder to distribute the fuel charge over the whole chamber by creating *violent turbulence* within it. Whether the proper atomization of the fuel is really due to impact of the two opposing sprays of fuel or whether the fuel is already sufficiently atomized when it leaves the fuel nozzles, is probably merely of academic interest. The fact remains that low fuel consumption is achieved and a lighter engine results due to the absence of an air compressor. Three American firms build engines of this type (Fig. 12) and a number of locomotives on American railroads use a high-speed engine of the same type as a propelling plant.

THERMODYNAMIC CONSIDERATIONS AFFECTING CAPACITY OF A GIVEN CYLINDER VOLUME TO BURN FUEL OIL AND DEVELOP POWER

Turbulence. Having now reviewed the structural changes employed by various designers to reduce the weight and space requirements of an oil engine, the author will now discuss the thermodynamic considerations affecting the capacity of a given cylinder volume to burn fuel oil and develop power. It has already been mentioned that fuel injection by air has many important advantages, as shown by indicated mean effective pressures up to 150 lb. per sq. in. being developed with but little if any smoking. When air injection is eliminated means for distribution of the oil charge must be adopted, and turbulence as used by Price or Deutz and Crossley in their so-called displacer engines is one of the instrumentalities employed to improve the lowered cylinder capacity. Furthermore, introduction

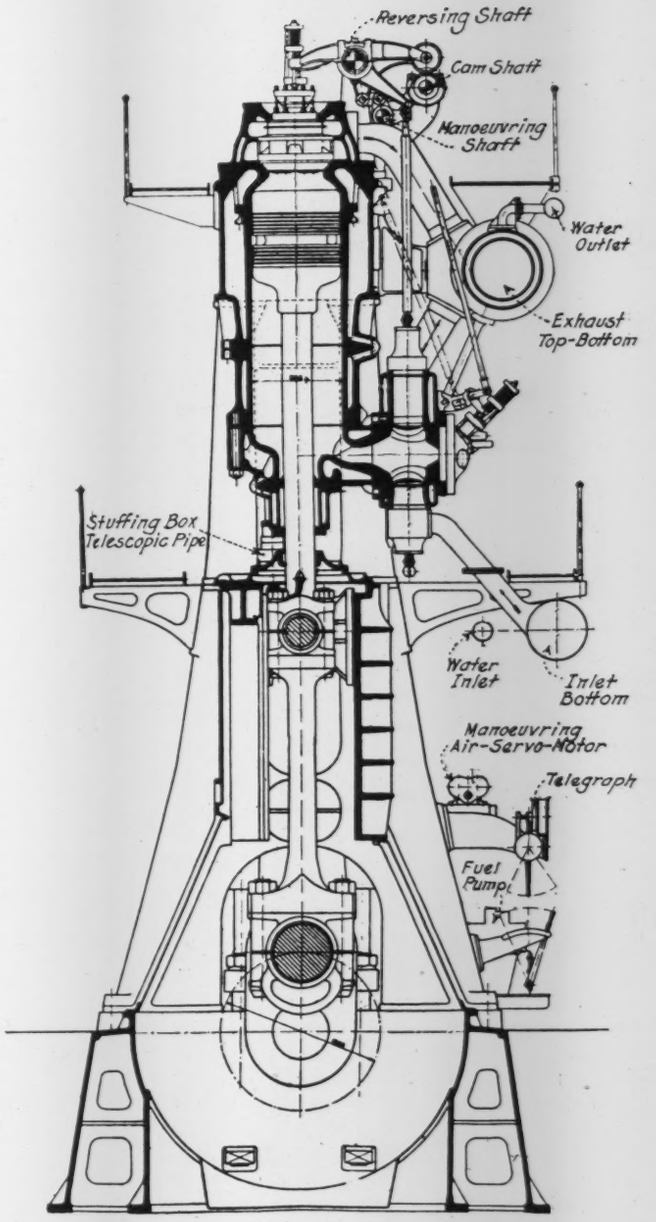

FIG. 7 CYLINDER SECTION OF WERKSPOOR DOUBLE-ACTING ENGINE (NEW DESIGN)

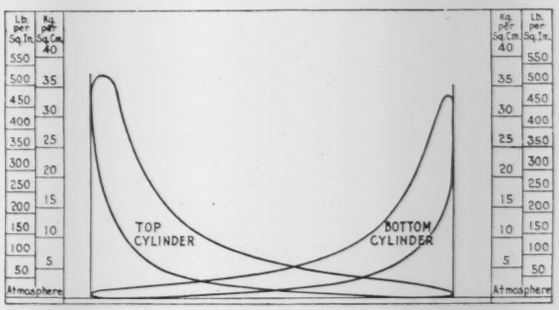

FIG. 8 INDICATOR CARDS FOR UPPER AND LOWER SIDES OF CYLINDER

of the combustion air into the cylinder in such a way that it enters in a spiral whirl tends to maintain such whirling motion even after it is compressed, and results in better fuel consumption and improved cylinder capacity as shown by the experiments on the Hesselman engine already referred to.

Scavenging Clearance Space. Any increase in shaft and piston speeds unfavorably affects the amount of combustion air

[13] Among others, a paper by Dr. Lucke in MECHANICAL ENGINEERING, Oct., 1921, p. 654; The Diesel Engine of Today (in English), Dr. Naegel, *Zeitschrift des Vereines deutscher Ingenieure*, June, 1923; also papers in same journal by G. Eichelberg (Aug. 7, 1926, p. 1079), and by Modersohn (Jan. 5 and 26, 1926, pp. 767 and 891), the latter being abstracted in *Journal of the American Society of Naval Engineers*, Nov., 1926.

[14] *Oil Engine Power*, May, 1926, p. 281.

[15] *Ibid.*, Nov., 1925, p. 652.

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that will find its way into the cylinder since velocities through the valves will also increase, assuming, of course, that the largest valves possible were installed in the first place. In addition the cylinder interior becoming hotter, the temperature of the incoming air increases and the amount (by weight) decreases still farther. Furthermore, normally not less than 7 per cent of the cylinder volume is filled with hot products of combustion from the preceding cycle that cannot be displaced by the upward-moving piston. There is also usually a slight overlap between the closing of the exhaust valve and the opening of the inlet valve which permits a certain amount of exhaust gases to get into the cylinder since the exhaust header is under slight pressure. Thus the loss of cylinder capacity is quite apparent. The recovery of this loss was the subject of experiments both in this country by the Falk Company[16] and in Germany. The inlet valves for this purpose are connected to a closed manifold, where a pressure of about 15 lb. abs. is maintained by a blower. This will result in a thoroughly scavenged clearance volume due to the above-mentioned overlap in valve timing and the fact that all of the cylinder volume is filled with pure air of atmospheric or slightly higher pressure. At the last meeting of the V.D.I. (Society of German Engineers) the statement was made that such scavenging of clearance volume permits of a 38 per cent increase in power as compared with unscavenged operation.[17] Such remedy will involve of course the use of some blower, whether of the rotary or Roots[18] or centrifugal[19] type, which may be either geared as the first one or driven by an electric motor, steam turbine, or exhaust-gas turbine.[20]

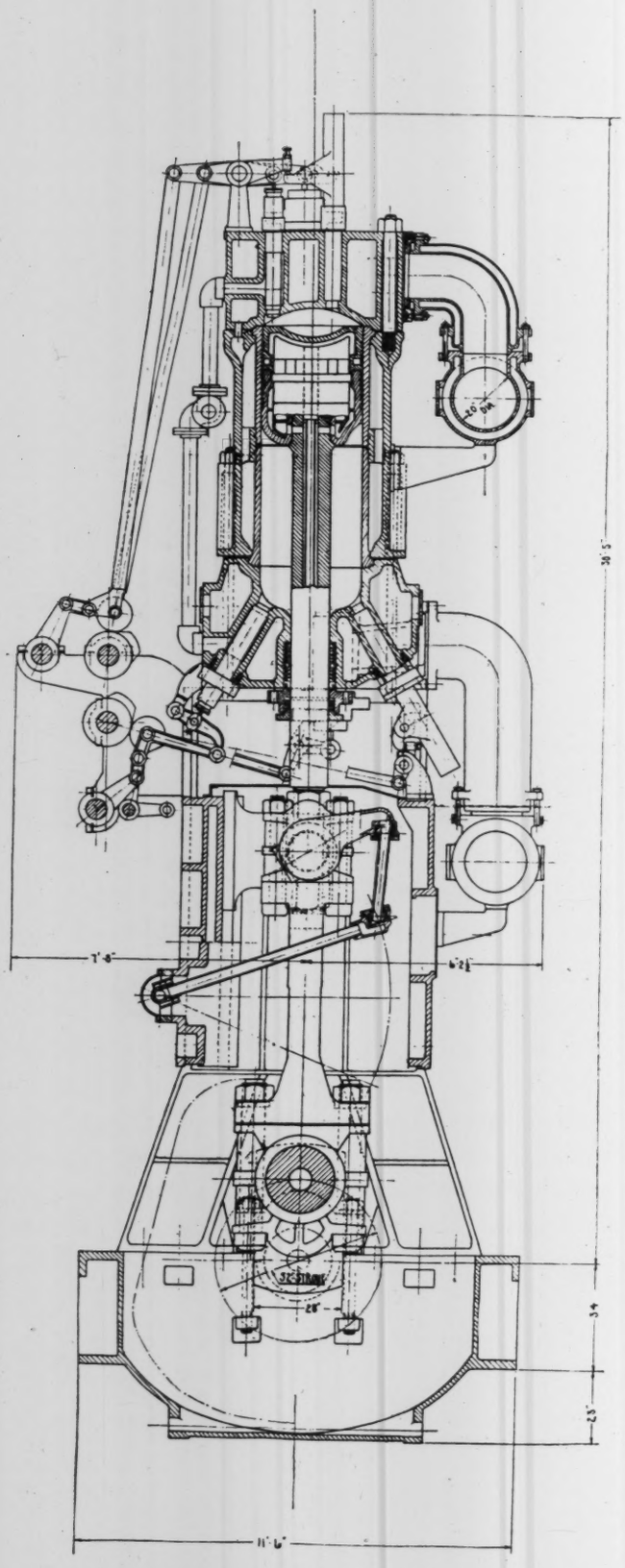


FIG. 9 SECTION OF THE MCINTOSH & SEYMOUR DOUBLE-ACTING ENGINE

This apparent additional complication will hardly be objectionable if the blower is reliable and the possible gain in power is as large as claimed.

Supercharging. Necessity is the mother of invention, and though much was done during and immediately following the war to increase the power output of aircraft engines at high altitudes by means of supercharging, this stimulus of itself was not sufficient to convert oil-engine builders to its use, though experiments[21] conducted tended to show its value. It was when a motorship could not meet its guaranteed speed, because the engines installed proved to be too small, that supercharging had to be resorted to to save the face of the builders.[22] A supercharging pressure of 0.85 lb. per sq. in. was maintained by a blower using 33 kw., and this increased the engine output by 500 i.hp. (16 per cent) and the speed of the ship from $10^1/_2$ to $11^1/_2$ knots. The success of this practice led to its adoption for the sister ships[23] and later for the high-speed gear-driven plant for ship propulsion to reduce the specific weight of the installation[24] by increasing engine output from 1350 to 1750 b.hp. (30 per cent)—No. 14, Table 1. The Italian licensee of the Burmeister & Wain Company resorted also to supercharging to increase the output of double-acting engines of the same dimensions as in the *Gripsholm*, but using 8 cylinders, from 9000 to 10,000 b.hp. (11 per cent)—No. 15, Table 1—retaining the high piston speed and driving the injection-air compressor by means of separate engines.[25]

Engines of substantially the same construction as used in the German submarines—No. 1, Table 1—are reported to have been installed with supercharging equipment furnishing air of substantially higher pressure, and having the resultant extremely low specific weight.[26]

Increase in Exhaust Temperatures. The objectionable feature of any effort to increase the specific capacity of the cylinder volume is the undesirable increase in exhaust temperatures, but with efficient combustion at the beginning of the stroke (no after-burning) the existing designs of cylinder heads and exhaust valves discussed earlier are apparently capable of coping with the situation arising from supercharging with blower pressures up to 15–16 lb. per sq.

[16] *Motorship* (N. Y.), Oct., 1924, p. 734.
[17] Prof. Magg in *Zeitschrift des Vereines deutscher Ingenieure*, Aug. 7, 1926, p. 1090.
[18] See N. A. C. A. Report No. 230.
[19] See Dr. Moss's paper in MECHANICAL ENGINEERING, Mid-Nov., 1925, p. 1076.
[20] *Motorship* (N. Y.), March, 1925, p. 203; *The Motorship* (British), May, 1926, p. 61.
[21] By Dr. Riehm of M.A.N.; see *Zeitschrift des Vereines deutscher Ingenieure*, Aug. 4, 1923, p. 763, abstracted in *The Motorship* (British), Nov., 1924, p. 294.
[22] *Motorship* (N. Y.), Mar., 1921, p. 179.
[23] *The Motorship* (British), Nov., 1924, p. 291 and 294.
[24] *Monte Sarmiento* and *Monte Olivia*. *Motorship* (N. Y.), Dec., 1924, p. 308, and Feb., 1925, p. 100.
[25] *Saturnia* and *Urania*. *Motorship* (N. Y.), Feb., 1926, p. 98.
[26] *The Motorship* (British), Aug., 1926, p. 181.

in. Further increase in supercharging pressure if considered from the standpoint of fuel economy is very limited, since the energy of the exhaust gases would soon be insufficient to drive the supercharging blower, and fuel consumption would suffer. But for the same reason the steam engine with atmospheric exhaust should have no place in our industrial life, yet countless thousands of horsepower are developed in such manner in locomotives alone. Is it not logical, then, to conclude, that if substantial increase in the horsepower of an oil engine without endangering its reliable performance is possible by supercharging, supercharging is the proper solution for the propelling plant of a warship, for instance, where the maximum speed is needed but rarely and where every pound of weight counts? The details of any such plant may include variable clearance volume with auxiliary fuel injection, or two different clearance volumes for the two ends of a double-acting cylinder, with one side permitting a high degree of supercharging or running idle when it can be spared, while the other works on the standard self-induction cycle. Success in such a research would be a most generous reward for the patience and foresight of an engineering executive and the perseverance of his staff.

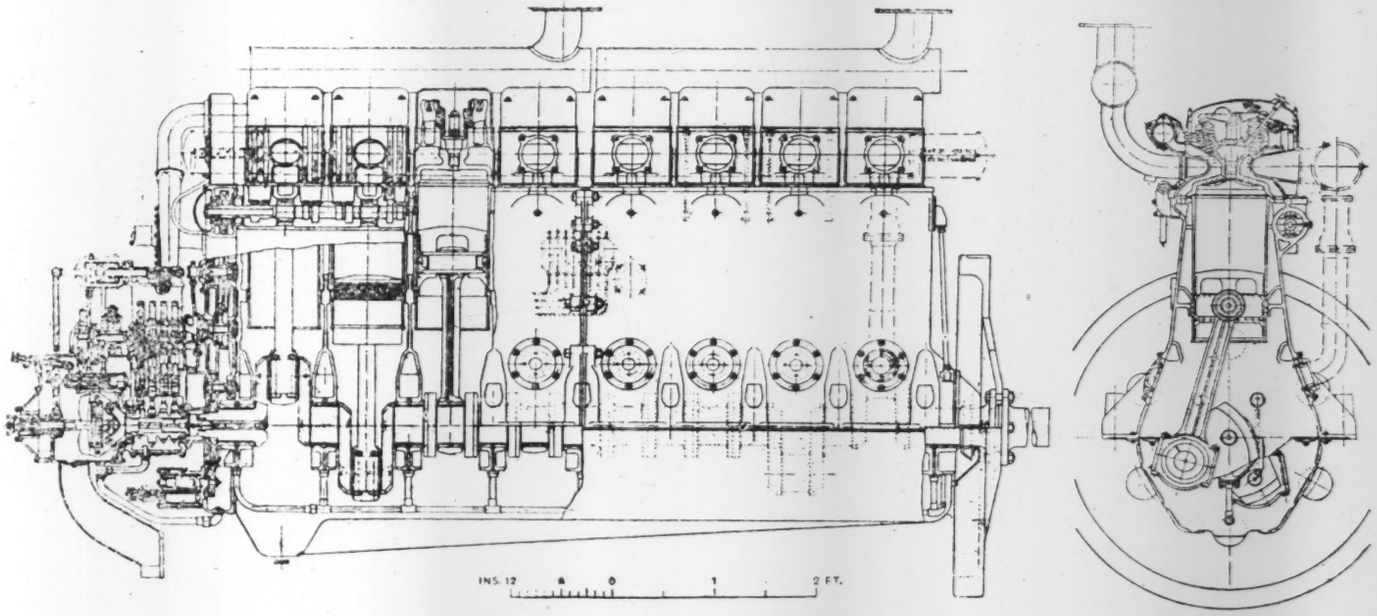


FIG. 10 BEARDMORE HIGH-SPEED LOCOMOTIVE ENGINE

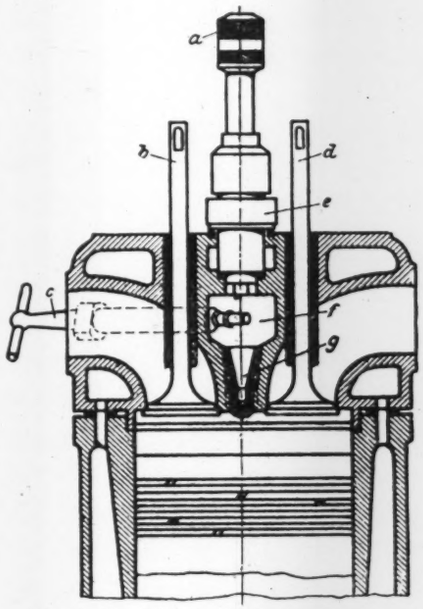


FIG. 11 A TYPE OF INJECTION CHAMBER USED BY BENZ CO.

II—TWO-CYCLE ENGINES

As has been mentioned in the opening paragraphs of this paper, oil engines using the two-stroke cycle burn roughly twice the amount of fuel for the same cylinder volume and develop about twice the power. Hence the working cylinder weight per horsepower is considerably reduced, provided there are no practical obstacles to using such a method of improve the efficiency of material.

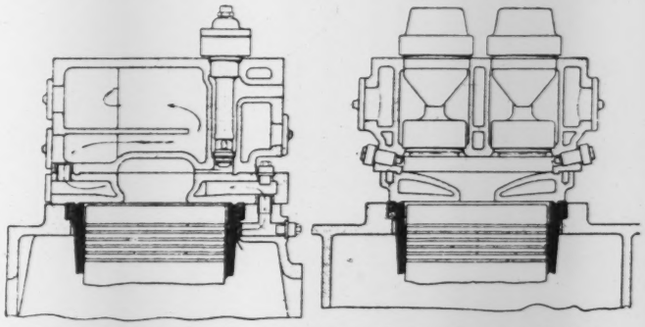


FIG. 12 COMBUSTION CHAMBER OF AN ENGINE BUILT BY FALK CO.

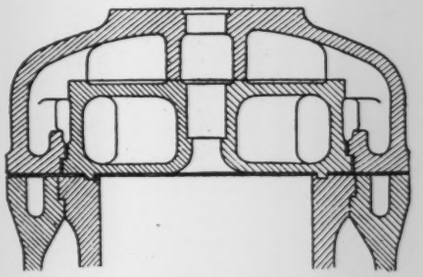


FIG. 13 TYPE OF HEAD USED ON NORDBERG-CARELS ENGINE

There have been difficulties, and many of them, so many in fact that a large number of two-cycle-engine manufacturers, especially of engines of moderate output, have been and are now content with much greater specific engine weight, as evidenced by the small brake mean effective pressure of their ratings, as long as the fundamental simplicity of two-cycle design and reliability of engine performance are maintained. The chief difficulty lies in accomplishing that which takes the four-cycle engine two out of every four strokes, or one-half of its time, to do, namely, scavenging and charging. The real problem is to do this in as short a time as possible and as efficiently—and even possibly more efficiently—as it is done in the four-cycle engine. In the absence of such

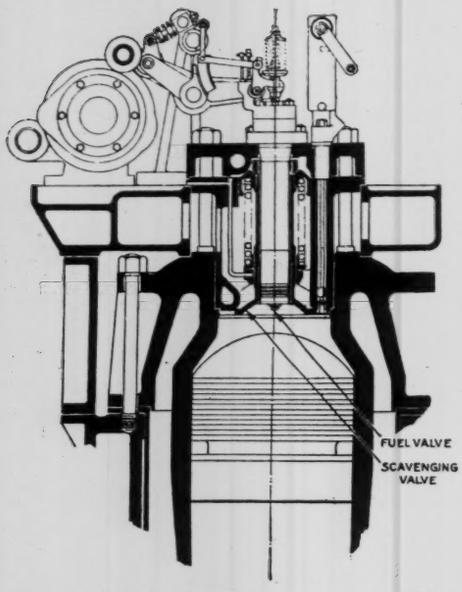


FIG. 14 SECTION THROUGH CYLINDER AND HEAD OF BETHLEHEM ENGINE

conditions as are present in the four-stroke cycle, a great many widely different solutions have been proposed; and a considerable number of them have survived and are being further developed to meet the more acute competition of the four-cycle engine and the more severe requirements of the time as to weight and space.

METHODS OF SCAVENGING

Methods of scavenging may be divided into two groups, namely, those where scavenging air charges the cylinder without changing its direction of flow, driving the exhaust gases ahead of it (like in a uniflow steam engine), and those where it reverses or otherwise changes its direction of flow. The first may be further subdivided into those employing valves in the cylinder head and ports at the bottom of the cylinder, and those using ports at both ends of the cylinder. The second group is confined only to the use of ports at the lower end of the cylinder, though a number of modifications of the relative positions of the two types of ports are in existence.

Valves in Head. A number of high-speed engines for U. S. submarines[27] of the M.A.N. step-piston type using one and later two valves in the head for scavenging have demonstrated that as far as cylinder scavenging is concerned this type operated quite reliably. The use of a stepped piston for pumping scavenging air gave rise to difficulties that resulted in the adoption by the M.A.N. company of the further developed, hence more reliable, four-stroke cycle for the German submarine engines, then badly needed due to the breaking out of the war. Valve scavenging when applied to cylinders of large diameter such as those of the M.A.N. type on the U.S. naval tanker *Maumee*[28] (No. 1, Table 2), was not successful due to cylinder heads failing under the excessive heat stresses. Changes in design and material did not solve the *Maumee's* troubles, but some other builders when confronted with similar experience were more successful in finding remedies.

The largest cylinder output so far built and incorporated into a full-size engine—2000 b.hp.—is that of the M.A.N. double-acting 12,000-hp. engine (No. 2, Table 2) for warship propulsion;[29] this engine used valves for scavenging, although they were located on the periphery of the cylinder and not in the cylinder heads

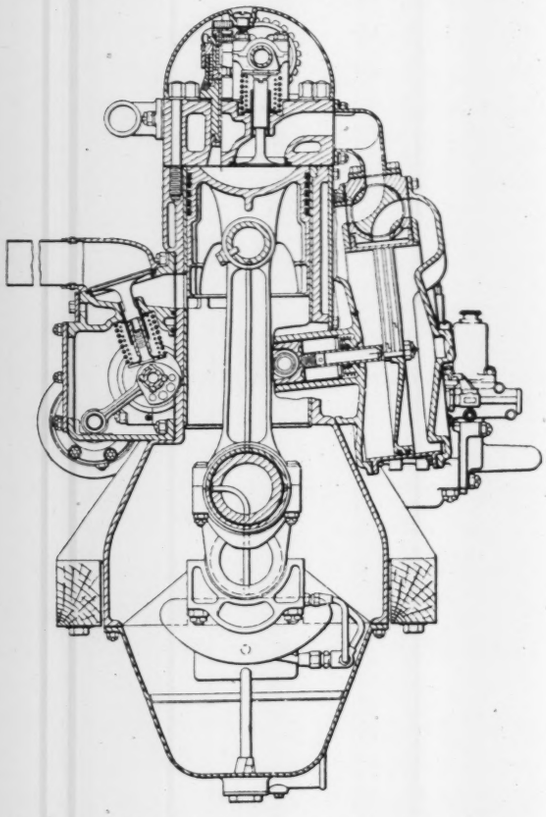


FIG. 15 SECTION THROUGH ATTENDU AIRCRAFT ENGINE

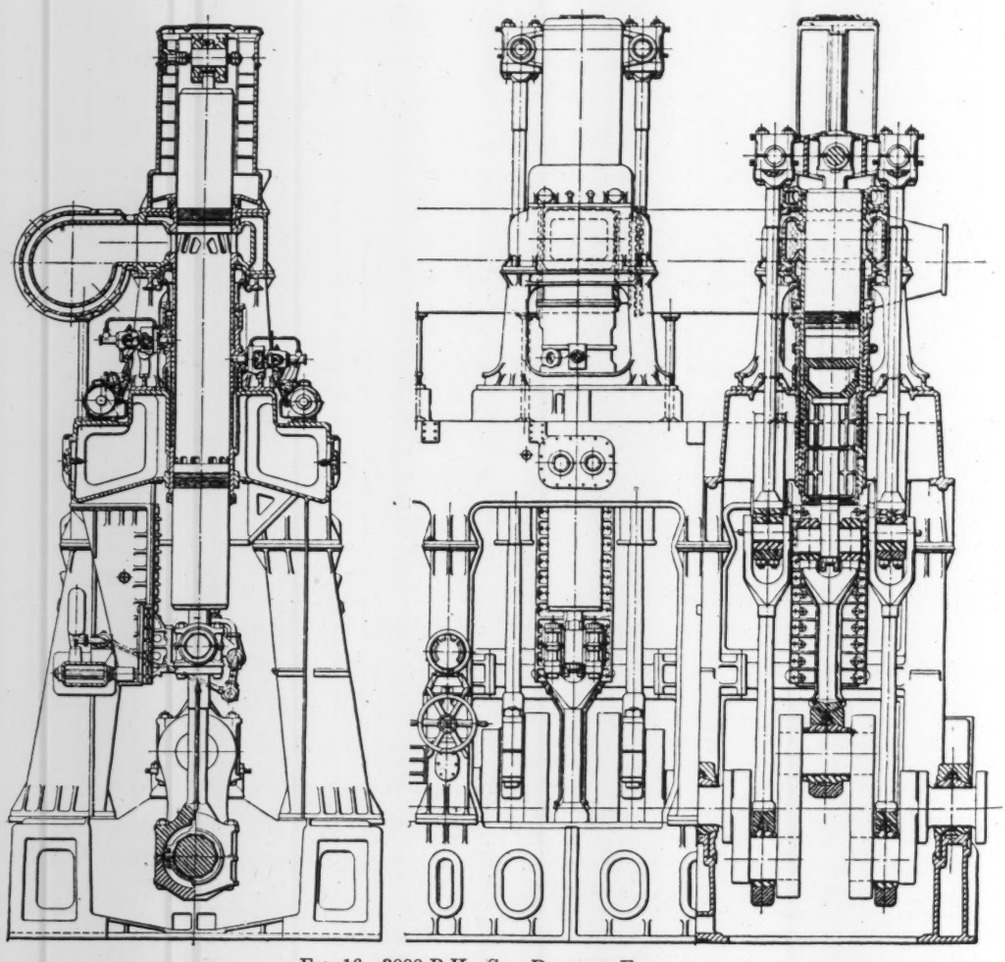


FIG. 16 3000-B.HP. SUN-DOXFORD ENGINE

[27] *Jl. Am. Soc. Nav. Eng.*, Aug., 1925, p. 583.

[28] *Jl. Am. Soc. Nav. Eng.*, Nov., 1915, p. 794.

[29] See *Zeitschrift des Vereines deutscher Ingenieure*, Dec. 8 and 22, 1923; *Motorship* (N. Y.), Jan., Feb., and Mar., 1924.

to save headroom. The largest stationary engine built in this country (for the Panama Canal)[30]—No. 3, Table 2—is of this type, as well as many other large engines of the same type, for example, the Nordberg-Carels. Here the solution appears to have been found in the use of a two-piece cylinder head (Fig. 13). The inner one, exposed to the heat of the combustion, is made of cast steel, as simple as possible and free to expand, whereas the cylinder-head bolts pass through the heavy outer head made of cast iron and serving as part of scavenging receiver. Another successful solution is that by the Krupps, who introduced a separate water-cooled shield to protect the heat-exposed surface of the cylinder head, a device they have retained even in their double-acting port-scavenging engine (Fig. 26), where the need of it, it would seem, is no longer apparent, and where also the two-piece cylinder head is used.

[30] *Oil Engine Power*, Feb., 1925, p. 77.

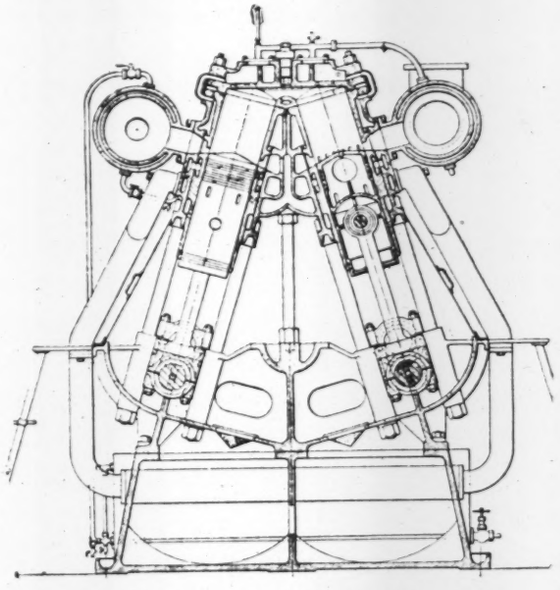


FIG. 18 CROSS-SECTION OF KNUDSEN OIL ENGINE

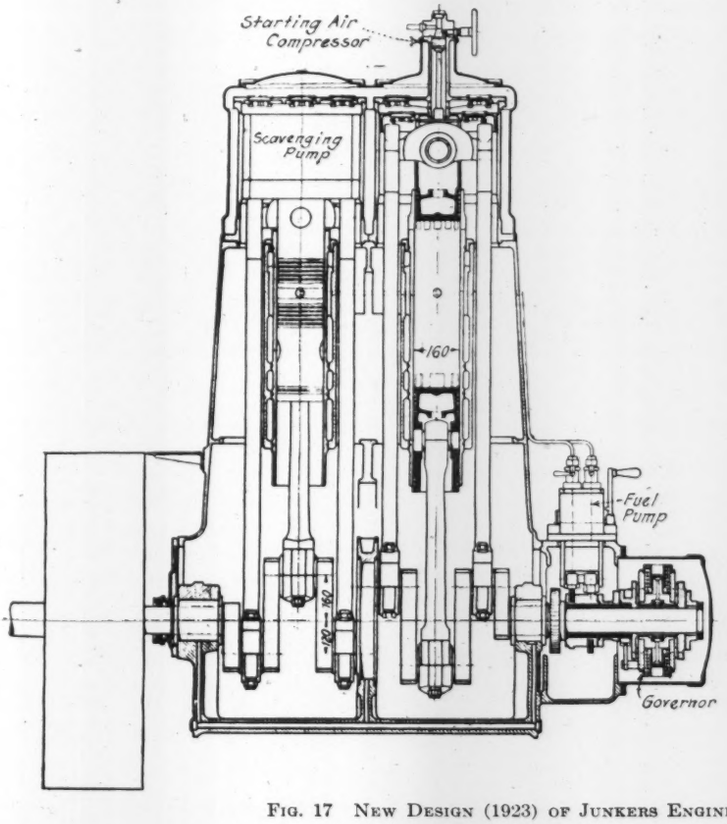


FIG. 17 NEW DESIGN (1923) OF JUNKERS ENGINE

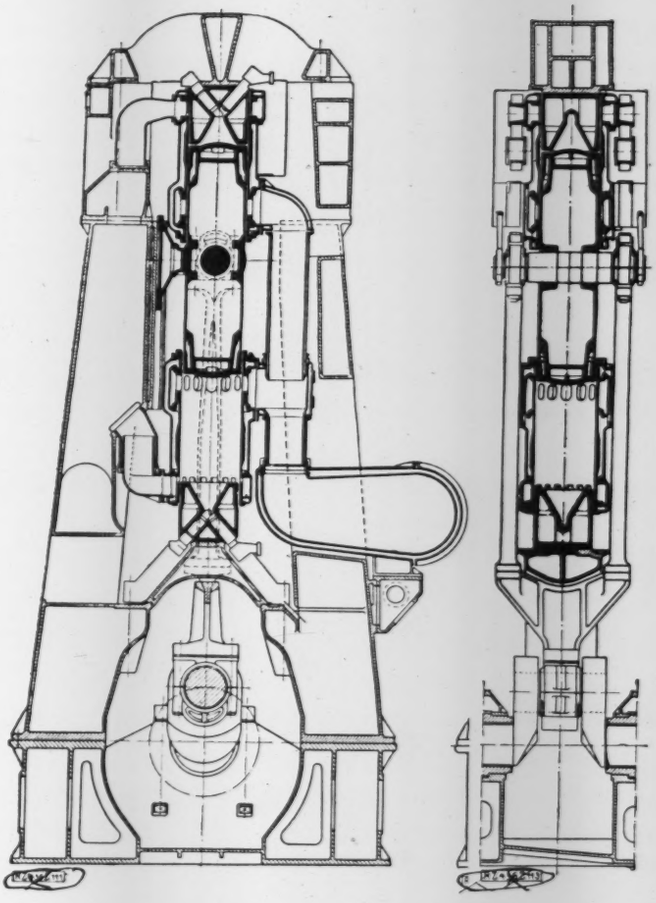
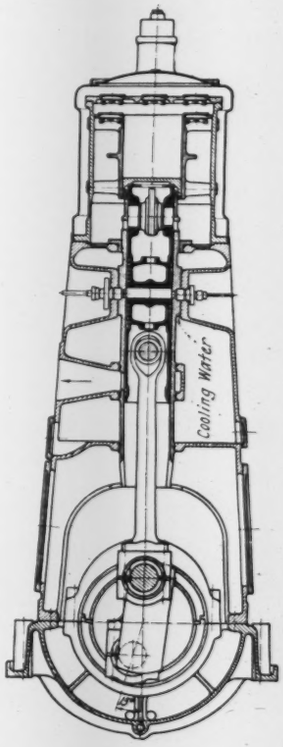


FIG. 19 SECTIONS OF NORTH BRITISH DOUBLE-ACTING ENGINE

This principle of providing free expansion for the parts of cylinder heads and cylinders is recognized in most of the new designs of two-cycle engines, and its adoption is probably largely responsible for their success.

An American engineer, Arthur West, is responsible for the Bethlehem Steel Company's solution of the scavenging problem[31] (No. 4, Table 2). A single centrally located scavenging valve of very simple dished shape admits the scavenging air (Fig. 14). A number of such engines are said to have been built both for marine and stationary power plants, and their successful operation will no doubt do much toward eradicating any existing prejudice against such an original and daring solution of the scavenging problem for the large oil engine.



Valve-in-the-head scavenging applied to cylinders of small diameter is not accompanied by any serious heat troubles, as was shown by the high-speed submarine engines. Its application to building an oil engine suitable for aircraft (Fig. 15), as was done by Attendu,[32] will, it is hoped, contribute much to the solution

[31] *Motorship* (N. Y.), March, 1924, p. 198; also March, 1926, p. 211.

[32] *Journal S.A.E.*, Feb., 1926, p. 1.

of high-speed light-weight oil-engine problems (No. 5, Table 2).

Opposed-Piston Engines. Ports have also been used to obtain the same individual flow of scavenging air and with a much smaller loss due to throttling of the air passing through the restricted areas of the admission organ. The size of valves is limited by the space available in the cylinder head and the lift by the acceleration of the valve mass which it is safe to use, whereas ports may occupy all of the periphery of the cylinder, and their height need be only somewhat smaller than for the exhaust ports. Furthermore, ports offer the opportunity of so shaping them that initial whirling motion by the scavenging air is obtained. This not only tends to better displacement of the exhaust gases but also creates turbulence which is so important for complete combustion, especially when no injection air is used. Opposed pistons inherited from gas-engine practice have been used by Junkers and Fullagar, each of the pistons controlling one set of ports. The sliding cylinder, the stroke of which is only sufficient to uncover the upper or scavenging ports, has been incorporated by Maclagan in the design of North British type of oil engine.

The Junkers Engine possesses other features of exceptional merit such as complete balance of reciprocating masses, relief of cylinder shafts are employed, direct-connected to the load, such as propellers in the aircraft type of engine, said to have been developed by Junkers.

A modification of the Junkers engine aiming at doing away with the multiplicity of cranks is the Fullagar engine, built by the Camellaird-Fullagar Co. and its licensees[36] (No. 9, Table 2). Here the cylinders are built in pairs close together with one crank for each, and each crank receives alternately the pressures of one upper and one lower piston, the two being connected with each other by diagonally slanted rods. Air injection of fuel has been retained by the builders of this type of engine. Excellent fuel consumption (0.39 lb. per b.hp-hr.) and very economic utilization of the cylinder volume, with a corresponding light weight and compactness, have been obtained in this type of engine, and a very large engine—10,000 b.hp. in 8 cylinders[37]—has been designed, but so far not built. However, the reported removal of engines of this type from the electric-driven motorship *La Playa*[38] without any cause being specifically published, leads to the suspicion that the existing design is not free from weak spots imperiling the reliable performance of the engine.

A further modification of the Junkers engine is the Knudsen

TABLE 2 DATA ON TWO-CYCLE ENGINES[1]

No.	Type of engine	S.A. or D.A.	No. of cylinders	B.Hp. Total	B.Hp. One cylinder	Bore, in.	Stroke, in.	R.p.m.	Piston speed, ft. per min.	Brake M.E.P. lb. per sq. in.	Specific volume cu. ft. per hp-min.	Weight, lb. Total	Weight, lb. Per b.hp.	Remarks
1	M.A.N.-*Maumee*	S.A.	6	2500	417	25.20	39.37	130	853	64.8	3.55	822,000	328	
2	M.A.N. (1917)	D.A.	6	12,000	2000	33.46	41.34	160	1100	71.7	3.19	.....	...	
3	Nordberg-Carels	S.A.	6	3750	625	29.0	44.0	125	917	68.5	3.41	815,000	218	
4	Bethlehem	S.A.	6	2900	483	25.5	48.0	116	928	67.5	3.41	.....	...	
5	Attendu	S.A.	2	85	42.5	5.5	6.5	1620	1755	67.4	3.40	477	4.9	
6	Sun-Doxford	O.P.	4	3000	750	23.62	91.34[2]	85	647	87.0	2.64	.....	...	Separate scavenging blower
7	Doxford-Submarine	O.P.	1	300	300	14.5	28.3[2]	300	707	84.8	2.70	.....	...	
8	Junkers (1923)	O.P.	2	120	60	6.3	12.6+9.45	375	788 max.	92.3	2.48	7700	64.0	
9	Palmer-Fullagar	O.P.	6	3000	500	23.0	36 + 36	90	540	73.5	3.12	.....	...	
10	Knudsen-Baldwin	Duplex	6 Twins	1000	167	9.75	13.5 + 13.5	450	1010	72.7	3.14	.....	...	
11	North-British	D.A.	3	2000	667	24.5	44.0	100	733	63.0	3.6	448,000	224.0	
12	Krupp-1917	D.A.	6	12,000	2000	34.4	41.35	140	965	68.4	3.35	.....	...	10,600 b.hp. only obtained on test
13	Worthington	D.A.	4	2900	725	28.0	40.0	95	633	64.8	3.74	600,000	207.0	
14	Worthington	D.A.	4	950	238	16.0	24.0	165	660	62.0	3.68	162,000	170.0	
15	Nobel	S.A.	4	1600	400	26.6	36.2	105	634	75.0	3.06	380,000	238.0	
16	Peugeot-Tartrais	S.A.	2	53	26.5	4.7	5.9	1450	1430	70.5	3.25	530	10.0	
17	M.A.N.	D.A.	6	4400	733	27.56	47.24	84	661	64.8	3.53	900,000	204.0	
			6	6250	1042	27.56	47.24	120	945	64.6	3.55		174.0	M.A.N. rating
18	M.A.N.	D.A.	6	7000	1167	27.56	47.24	125	985	69.2	3.31	1,090,000	155.0	Italian rating (M. S. *Augustus*)
19	Blohm & Voss-M.A.N.	D.A.	9	15,000	1670	33.8	59.05	94	934	69.2	3.31	.....	...	
20	Krupp	D.A.	1	1600	1600	31.5	59.05	85	836	84.4	2.69	.....	...	Without air compressor
21	Sulzer Bros. (1914)	S.A.	1	1600	1600	39.375	43.31	115	830	105.0	2.2			
				2000	2000	39.375	43.31	150	1070	101.5	2.27	.....	...	
22	Sulzer Bros.	S.A.	10	5800	580	26.8	47.24	100	787	86.2	2.66	.....	...	
23	Brown-Sulzer	S.A.	4	4000	1000	35.43	63.0	86	903	74.2	3.08	.....	...	
24	Busch-Sulzer	S.A.	6	3000	500	30.0	52.0	90	780	59.8	3.83	.....	...	

[1] Ten per cent allowance made for piston-rod area.
[2] Combined stroke.

and engine framing from explosive stresses, and absence of cylinder heads, which also tend to reduce its specific weight as well as does the employment of the two-stroke cycle. However, the German licensees of Junkers failed to get results chiefly because of their inexperience in oil-engine building in general, and only Doxfords in England under the guidance of Junkers' associate have achieved commercial success. The Doxford engine,[33] built in this country by Sun Shipbuilding & Dry Dock Company (Fig. 16), has been further lightened by the elimination of the injection-air compressor and the substitution of mechanical injection (No. 6, Table 2). During the war an effort was made to adopt this type of engine for submarine propulsion and an experimental cylinder was built and tested[34] in the Admiralty Engineering Laboratory without, however, any further results due to cessation of hostilities (No. 7, Table 2). This foreign success led Junkers to work out a new design[35] for his engine (Fig. 17), that also employed mechanical injection and in compactness of arrangement suggested a low-pressure steam engine (No. 8, Table 2). The lowest fuel economy ever achieved in any oil engine, 0.345 lb. per b.hp-hr., is claimed to have been obtained with this engine. A serious objection to this type of engine is the fact that it does not lend itself to very high rotative speeds due to the inevitable heavy weight of the upper piston and masses reciprocating with it unless two separate crank-engine (Fig. 18) installed by the Baldwin Locomotive Co. in their locomotive[39] (No. 10, Table 2). However, here most of the above-named advantages of the opposed-piston designs have been sacrificed and only the one-direction (uniflow) scavenging retained, although the disadvantage of unequal reciprocating weights also disappears and the engine has been built as a high-speed engine. Furthermore, by placing the two crankshafts so close together their interconnection by means of gears has become feasible and has been employed. Whether the cylinder head containing the common combustion chamber will stand up under severe heat stresses, whether air cooling of pistons is sufficient, and whether torsional-vibration problems arising in such a high-speed gear-driven machine, as mentioned already, have been properly taken care of will be answered by extended operation of this engine unit in service.

Sliding-Cylinder Engine. To obtain the advantages of uniflow scavenging with scavenging ports of large area, Maclagan proposed the sliding-cylinder type of engine, and a double-acting engine of this type consisting in reality of two separate single-acting cylinders in tandem has been built by the North British Diesel Engine Works[40] (Fig. 19), and two more have been installed in motorships (No. 11, Table 2). Whether such radical departure from more

[33] *Motorship* (N. Y.), Sept., 1924, p. 652.
[34] *The Engineer*, May 4, 1923, p. 489.
[35] *Zeitschrift des Vereines deutscher Ingenieure*, Oct. 31, 1925, p. 1369; also *Oil Engine Power*, Dec., 1925, p. 696.
[36] *The Motorship* (British), March, 1924, p. 470; Sept., 1924, p. 200; Oct., 1924, p. 231; and *Motorship* (N. Y.), Dec., 1923, p. 854, and Feb., 1924, p. 118.
[37] *The Motorship* (British), Nov., 1924, p. 276.
[38] *The Motorship* (British), Nov., 1923, p. 281; and *Motorship* (N. Y.), Aug., 1926, p. 597.
[39] *Oil Engine Power*, Sept., 1925, p. 523.
[40] *The Motorship* (British), May, 1923, p. 42, and Nov., 1924, p. 284.

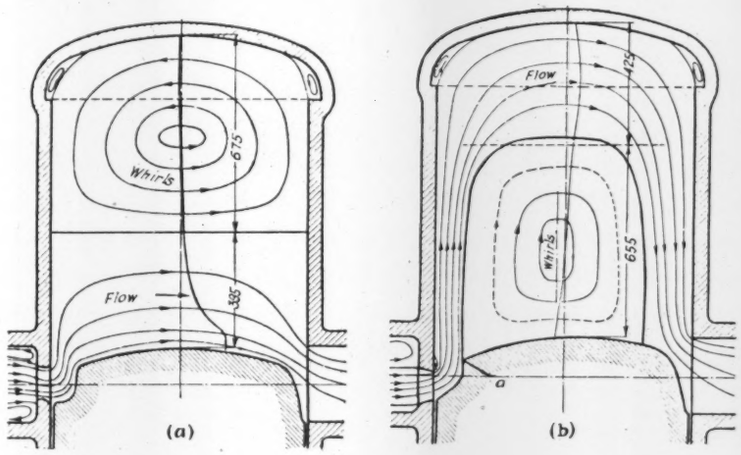


FIG. 20 STREAMS OF SCAVENGING AIR AND WHIRLING LOOP OF EXHAUST GASES IN THE KRUPP 12,000-HP. ENGINE (*a*) WITH ORIGINAL PISTON AND (*b*) AS MODIFIED

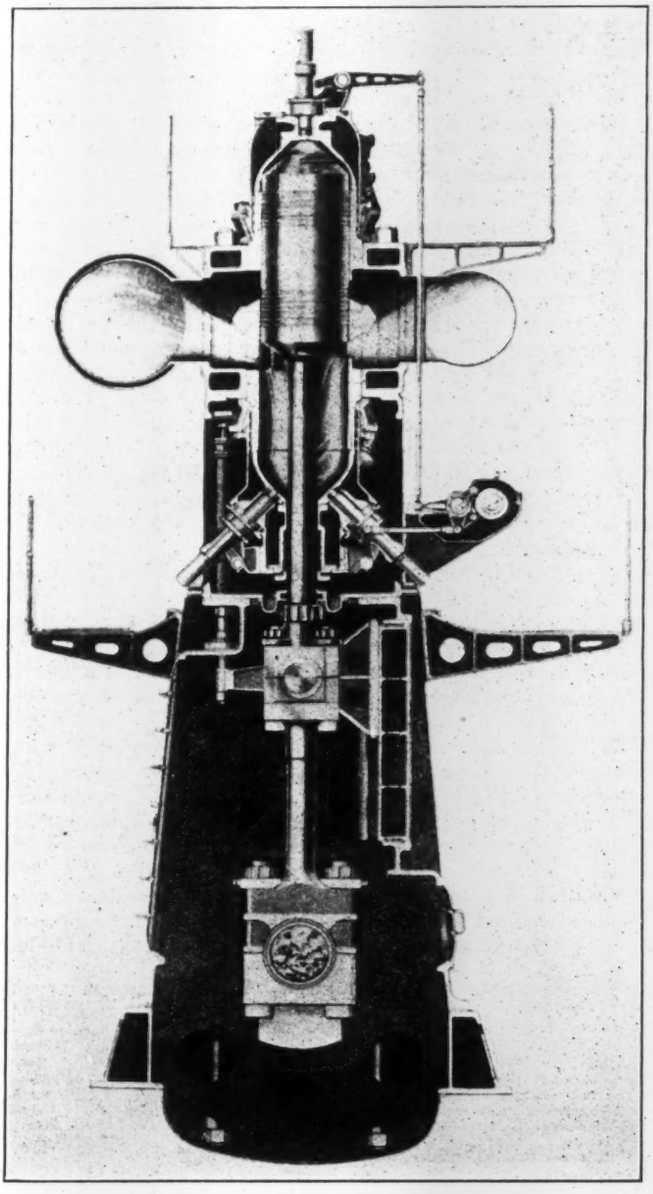


FIG. 21 CROSS-SECTION OF THE WORTHINGTON DOUBLE-ACTING ENGINE

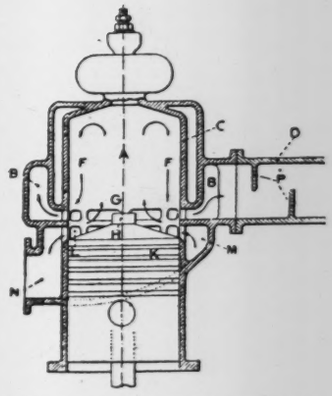


FIG. 22 SCAVENGING METHOD USED BY TARTRAIS IN PEUGEOT ENGINE

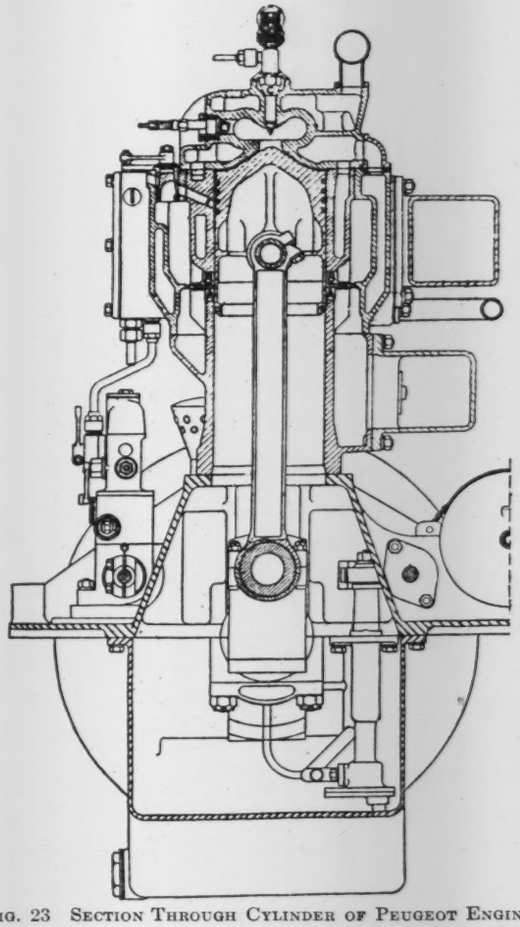


FIG. 23 SECTION THROUGH CYLINDER OF PEUGEOT ENGINE

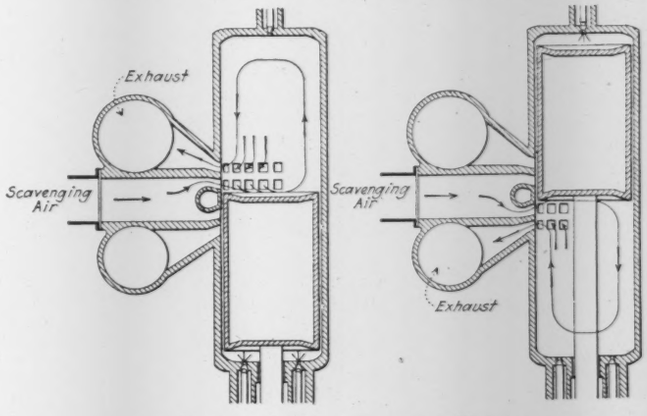


FIG. 24 M.A.N. LOOP-SCAVENGING SYSTEM

familiar forms is justified by the results obtained or that can be obtained with this construction, time alone can tell. It does appear, however, that the severe handicap of the natural prejudice of the operating engineer to radical departures will long hamper its development.

Port Scavenging. The possibility of dispensing with all valves is a most valuable feature of a two-cycle engine, long appreciated by builders of small engines for motor boats. Simplicity of such arrangement while valuable in rather small oil engines, where it is often paid for by substantial rise in fuel consumption and higher specific weight, becomes particularly important in large engines, where the valves and valve gear and its drive become important problems of design and maintenance. (A sticking scavenging valve was responsible for the explosion in the scavenging receiver of the large Nuremberg oil engine, resulting in the ruin of the engine and death of several attendants.[41]) Hence efforts to improve the scavenging obtained by the simple deflector of the scavenging air have been made, and this simple system is now used in such engines as Worthington (double-acting), Neptune, Still, and others.

To illustrate the difficulties in arriving at the right shape of that part of the piston that will control the flow of the scavenging air, two diagrams taken from the historical sketch describing the development of the Krupp 12,000-hp. engine (No. 12, Table 2) for German-warship propulsion[42] are reproduced (Fig. 20). These clearly indicate the building up of a whirling loop either nearest the fuel valve (*a*) or directly above the receding piston (*b*), and the passing of scavenging air into the exhaust header without driving out the products of combustion and charging of the cylinder with fresh combustion air. The inevitable result of such action was that the engine could not develop its designed horsepower due to lack of air in the cylinder and smoky exhaust with high exhaust temperatures. Experiments with the Scott-Still engine scavenging have also shown that.[43]

The new Worthington double-acting engine[44] (Fig. 21) has enjoyed much deserved publicity both here and abroad mainly for its extreme simplicity, due largely to its method of scavenging. Its rating at first glance appears conservative (Nos. 13 and 14, Table 2), both as to piston speed and mean effective pressure, but the rather high fuel consumption obtained on test of the Shipping Board engines tends to indicate that the low efficiency of the method of scavenging and charging of the cylinder would hardly permit a much higher rating. But even with this handicap its specific weight is materially lower than that of any of its competitors on the S.B. program, and for the smaller engine recently installed[45] it is as low as in any engine of its class.

The same type of scavenging, with the addition of light automatic valves to prevent the cylinder contents from entering the scavenging receiver while exhaust by excess pressure in the cylinder takes place, is used in Nobel and Fiat engines. This feature permits the scavenging ports to be made of equal height with the exhaust ports, resulting in much better charging of the cylinder and consequently a lighter engine (No. 15, Table 2). An experimental high-speed, two-cylinder, 1000-hp. engine employing this type of scavenging has been built and successfully tested by the Fiat Co. for the purpose of developing a high-power engine for the Italian submarine,[46] but unfortunately no further data about it are available.

Loop Scavenging. The same simplicity of design with apparent improvement in charging of the cylinder has been obtained in engines using so-called loop scavenging. Tartrais has employed two rows of ports (Fig. 22), the exhaust ports being above the scavenging, all over the periphery of the cylinder. By giving a suitable shape to the piston crown he makes the opposing ports produce two parallel streams of scavenging air in the center of the cylinder. These are deflected by the cylinder head and return along the cylinder wall into the upper (exhaust) ports. This type of scavenging has been adopted by the well-known French builder of automobiles, the Peugeot Co. (Fig. 23), and recent protracted tests[47] on an improved model of this type testify to the efficiency of scavenging. The splendid fuel consumption obtained—0.451 lb. per b.hp-hr. at 1450 r.p.m.—is furthermore a tribute to the value of turbulence produced by this design of cylinder head, and shows the importance of continuous renewal of fresh air at the fuel valve (No. 16, Table 2).

A similar method of scavenging has been employed by the two foremost German oil-engine builders, M.A.N. and Krupp, in an effort to create a cylinder of very high capacity and of simple design, and therefore inexpensive to build. In the M.A.N. design[48] the two rows of ports (Figs. 24 and 25), the exhaust being above the scavenging, occupy only slightly over one-half of the periphery of the cylinder. The concave piston crown and the shape of scavenging ports produce a column of air along the unpierced part of the cylinder wall, which is deflected by the cylinder head and returns along the opposite wall to the exhaust ports. Krupp's modification[49] (Fig. 26) consists of having the higher exhaust ports along the axis of the engine, whereas the scavenging ports are on one side only, so that the scavenging-air column is also guided by the opposite wall but is split in two columns directed toward each set of exhaust ports. The scavenging efficiency is evident from the figures in the table, especially when allowance is made for the natural conservatism displayed by the rating of the first engines of the type.

Sulzer Type of Scavenging. A distinct type of scavenging was developed by Sulzer Bros. when this firm, realizing the possibilities of the two-stroke cycle, attempted to solve the problems of the valve scavenging originally adopted by them. The success of the Sulzer method of scavenging (Fig. 27) lies apparently in the fact that two separate streams of scavenging air traverse the interior of the cylinder, thus preventing any whirling loops from building up and effectively blowing out the burnt gases into the exhaust ports. Two sets of scavenging ports occupy about one-half of the cylinder periphery and have suitable guiding surfaces so as to scavenge both the upper part of the cylinder immediately at the fuel valve and the space above the piston. The exhaust ports occupy the opposite side of the cylinder. The upper scavenging ports are opened by the piston before the exhaust and are therefore equipped with light automatic valves (in new designs), whereas the lower are beyond the danger of admitting exhaust gases into the scavenging receiver and are piston-controlled only. An additional advantage of this type of scavenging is the ability to improve charging of the cylinder by filling it with fresh air from the scavenging receiver after the exhaust ports are closed, up to the pressure in the receiver. This supercharging feature will be dealt with later.

Sulzer Bros. appear to be consistently maintaining the position that the efficiency of their scavenging permits them to use smaller cylinders and, since they have demonstrated that a 2000-hp. single-acting cylinder can be built[50] (No. 21, Table 2), therefore there is no real need for a double-acting cylinder. At any rate their British licensee, Brown, built a single-acting engine of a cylinder capacity about equal to that offered by any builder of double-acting engines to date and of a smaller specific cylinder volume than any of the existing double-acting two-cycle engines. The American-built Busch-Sulzer engine for the Shipping Board suffers apparently from the conservatism of contract limitations.

The purpose of the preceding review has been to show how successful the oil-engine builders of the world have been in solving the problem of one of the most potent means of reducing weight and space required by an oil engine, namely, the use of the two-stroke cycle. In this connection Table 3 may be of interest as it reproduces

TABLE 3 AVERAGE VALUES OF PISTON SPEED, BRAKE M.E.P., SPECIFIC VOLUME AND SPECIFIC WEIGHT FOR OIL ENGINES

	Four-cycle		Two-cycle	
	Single-acting	Double-acting	Single-acting	Double-acting
Piston speed-ft. per min.	880 to 1240		790 to 950	
Brake m.e.p-lb. per sq. in.	71.0	64.0	78.0	62.5
Specific volume, cu. ft. per min. per hp.	6.0	6.7	3.18	3.53
Specific weight, lb. per b.hp.	330	220	265	200

[41] The Diesel Engine of Today, by Dr. Naegel, *Zeitschrift des Vereines deutscher Ingenieure*, June, 1923 (in English), also same journal Dec. 8 and 22, 1923, and *Motorship* (N. Y.), Jan., Feb., and Mar., 1924.

[42] *Zeitschrift des Vereines deutscher Ingenieure*, Nov. 15, 1924, p. 1203.

[43] *Motorship* (N. Y.), Dec., 1923, p. 871.

[44] *Motorship* (N. Y.), April, 1926, p. 270.

[45] *Marine Engineering*, Oct., 1926, p. 577.

[46] *The Motorship* (British), Oct., 1926, p. 247.

[47] MECHANICAL ENGINEERING, June, 1926, p. 615.

[48] *Motorship* (N. Y.), May, 1926, p. 367 and Oct., 1925, p. 747.

[49] *Werft-Reederei-Hafen*, Aug. 7, 1926, p. 388.

[50] *Engineering*, Aug. 25, 1922, p. 226.

average values of piston speed, brake m.e.p., specific cylinder volume, and weight given in a paper read before the last annual meeting of the Society of German Engineers by M. Gercke of the M.A.N. Company. These average values have been obtained from a large number of engines, but do not necessarily cover extremes of any type.

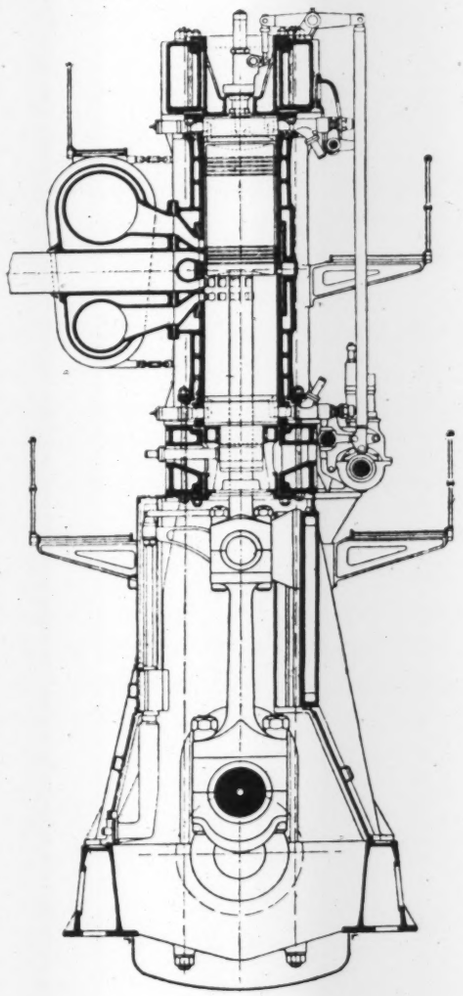


FIG. 25 SECTION OF M.A.N. DOUBLE-ACTING ENGINE

FURTHER MEANS OF IMPROVING WEIGHT AND SPACE REQUIREMENTS

High Speeds. Further means that may be employed to improve the weight and space requirements do not differ materially from those used on four-cycle engines and already reviewed. High rotative speeds as in the Attendu and Peugeot engines and a number of two-cycle submarine engines built by Sulzer Bros., Fiat Co., and by two French builders, have been employed. Unfortunately there is no published information available, although several different engines up to 6000–7000 hp.[51] have been reported in construction for the French Navy. The 2500-hp. Busch-Sulzer engine[52] installed in three U.S. fleet submarines is an example of this class. The Knudsen-Baldwin engine, which has already been discussed, makes also efficient use of the high rotative speed for weight reduction.

The Double-Acting Principle. The use of the double-acting principle in connection with two-cycle engines is spreading rapidly, and in the minds of a large number of oil-engine builders is the only means for meeting the demand for high-capacity engines. Vickers Ltd., for instance, after building a 2900-hp. single-acting four-cycle engine of their own design, purchased a license for building M.A.N. two-cycle double-acting engines. The Werkspoor Co. is reported to be experimenting with a double-acting, two-cycle engine at their home plant, notwithstanding the fact that they collaborated with their British licensee in building double-acting four-cycle engines.

Crank-Mechanism Modifications. Modifications in the standard crank mechanism play also an important role in the development of the two-cycle engine, such, for instance, as Junkers and Fullagar adopted. In this connection mention should be made of the Michel engine that is being developed in Germany. The original engine of this type is reported to have been in operation at the builder's works for four years. From the schematic representation in Fig. 29 it will be noted that three cylinders with a common combustion chamber are placed radially, one having exhaust ports while the other two admit scavenging air. At the ends of the piston rods are placed rollers running in a cam-shaped groove which is part of the flywheel. The whole is essentially a high-speed engine with a 3-to-1 reduction built into it. It is evident that if such an engine can be made to work so reliably that accessibility becomes

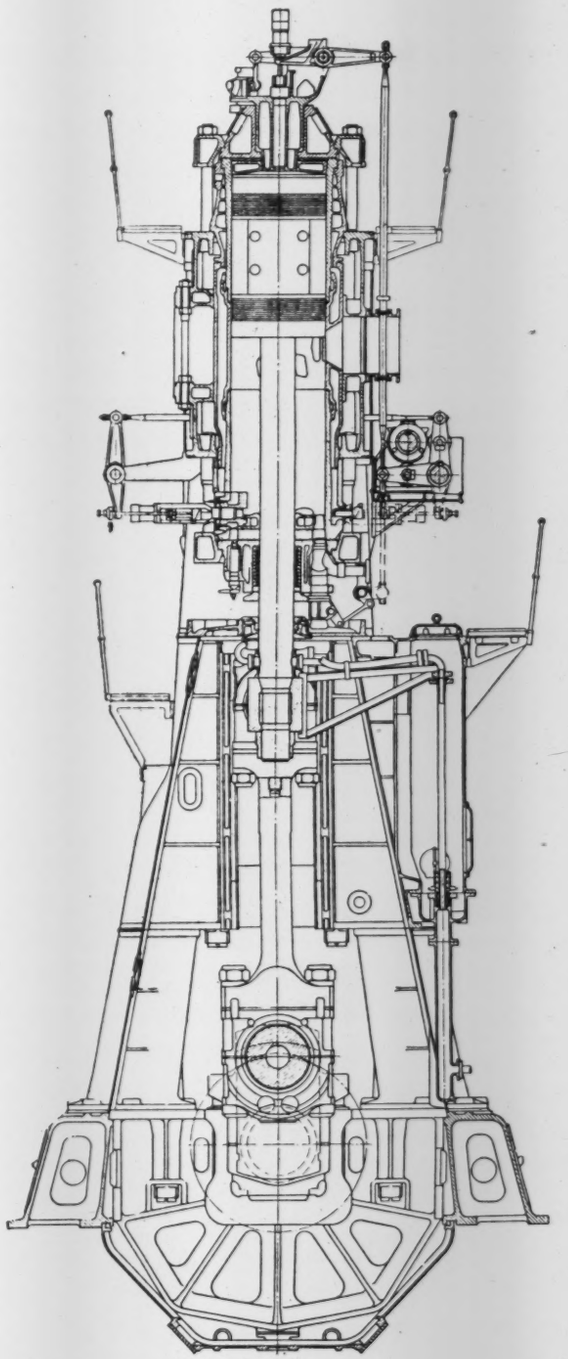


FIG. 26 SECTION OF KRUPP DOUBLE-ACTING ENGINE

[51] *Motorship* (N. Y.), Feb., 1926, p. 121.
[52] *Jl. Am. Soc. Nav. Eng.*, Aug., 1925, p. 583.

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a secondary matter, this solution is of far-reaching importance. But difficulties peculiar to such an unusual design no doubt developed, since no commercial installations of the engine have been reported.

Airless Injection of Fuel has been used on two-cycle as well as on four-cycle engines. Attendu, Peugeot, and Knudsen have used it on high-speed engines, and Doxford, Scott-Still, and Junkers have applied it also and with very pronounced success, as already mentioned. A large number of rather small-capacity engines are using injection chambers, and the great majority of larger engine builders are still experimenting with airless injection, and the announcement of its adoption may be expected any time as evident from a recent paper by Dr. Eichelberg[53] of Sulzer Bros.

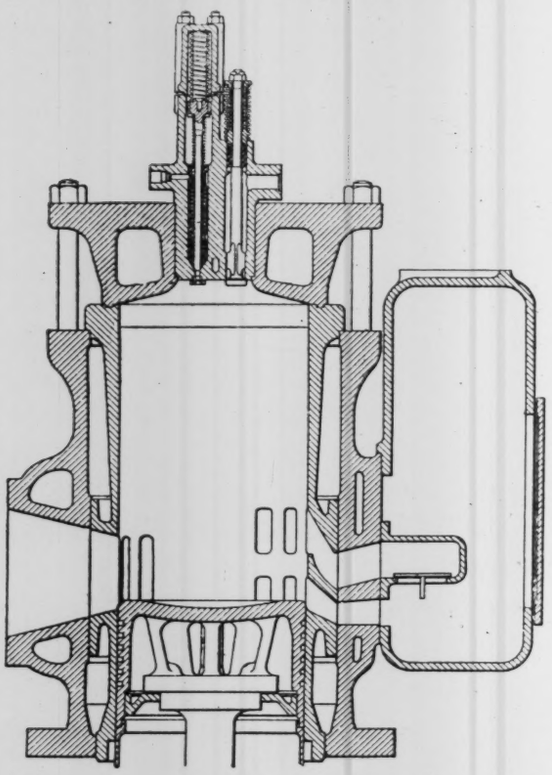

FIG. 27 SECTION OF THE SULZER TYPE OF CYLINDER, SHOWING SCAVENGING SYSTEM

Supercharging is really a feature of the two-cycle engine and is employed in a large number of such engines. With valve scavenging this is obtained by leaving the valves open a short time after the piston passes the exhaust ports, and here it is extensively used, especially in altitude installations, where a slightly larger scavenging pump restores the engine to its normal output. In opposed-piston engines and in the Knudsen engine this can also easily be done by suitable timing of the two pistons. The Sulzer engine permits supercharging by virtue of the upper scavenging ports closing after the exhaust ports. Supercharging as applied by two cycle-engine builders refers to filling the cylinder with scavenging air up to a pressure of about 15–16 lb. absolute, and the effect of supercharging is clearly visible on the indicator diagram of the Busch-Sulzer engine, built for the Shipping Board[54] (Fig. 28). Attempts to increase supercharging led to heat troubles at the weakest spot in the engine, as told by Mr. Knudsen at the last Annual Meeting of the Society.[55] Junkers, who also experimented considerably with high supercharges against back pressure, did not incorporate any such feature into any commercial engine.

Attempts at high supercharging cannot be promising so long as we have (*a*) no materials to withstand the added heat generated within the cylinder, and (*b*) no means of efficiently utilizing the heat rejected with the exhaust gases. These two considerations apply equally to four- and two-cycle engines, except that in two-cycle engines their need is greater. Thus the development of better heat-resisting materials will open up new avenues of experiment, and oil-engine development will follow.

Compound Engine. As to the utilization of the waste heat of the engine, aside from the rather inefficient use made of the exhaust gases in exhaust-gas boilers for heating purposes such as process water or building heating, this is done in the Still engine, where steam of 100 lb. pressure is generated from the jacket water by the exhaust gases and used on the under side of the piston, where by expansion it further abstracts heat and cools the piston. Except for the possible complication of the boiler, condenser, and feed pumps, this solution of the problem gives improved fuel consumption, though weight and space advantages are rather doubtful. Besides it appears to stand in real danger from the steam-engine advocates, who are apt to change it into a good steam engine with the oil engine only as a sort of standby.

When better materials are available the compound engine may become an attractive solution of the weight and space problem with good fuel consumption as an additional advantage. Compounding is nothing more than supercharging of the high-pressure cylinder coupled with an efficient utilization of its exhaust in the low-pressure cylinder. So far, however, the efforts of Mr. Sperry have not reached commercial success, chiefly due to the failure of the transfer valve. And when restricted by the capacity of this part to withstand heat, the compound engine offers no advantages to compensate, for instance, for such a practical disadvantage as multiplicity of different parts.

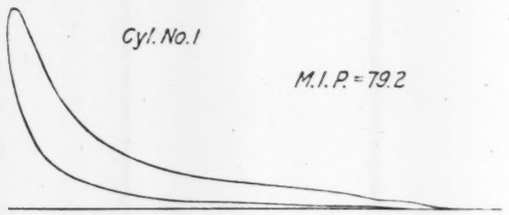

FIG. 28 INDICATOR CARD OF THE BUSCH-SULZER ENGINE, SHOWING SUPERCHARGING

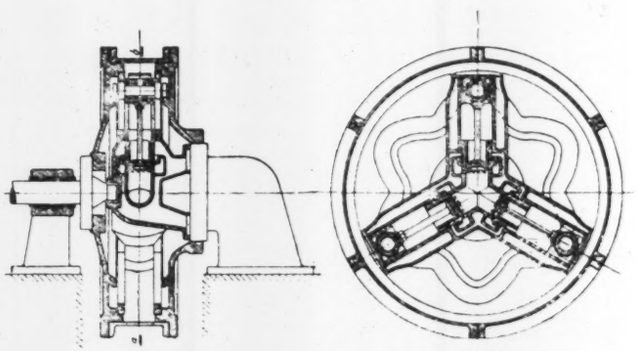

FIG. 29 MICHEL OIL ENGINE

CONCLUSIONS

The foregoing study of modern oil engines can properly be summed up as follows:

a Substantial progress in oil-engine development is not made by unduly stressing one particular line of attack.

b The combination of a number of means tending to improve the horsepower output of a given engine structure is necessary.

c High piston speeds combined with high rotative speeds where practicable, airless injection of fuel, and the use of high-speed blowers for furnishing combustion air in both four-cycle and two-cycle engines are more commonly employed.

d The double-acting two-cycle engine, due to the simplicity of port scavenging, is regarded as being better able to solve the large-engine problem than any other type.

[53] *Zeitschrift des Vereines deutscher Ingenieure*, Aug. 7, 1926, p. 1079.
[54] *Marine Engineering*, Oct., 1926, p. 579.
[55] MECHANICAL ENGINEERING, May, 1926, p. 474.

A Temperature-Entropy Diagram for Air and the Diatomic Gases O_2, N_2, and CO

By HAROLD A. EVERETT,[1] STATE COLLEGE, PA.

Accepting the summary of the data on the variation of specific heats with temperature as presented by Goodenough and Felbeck in 1924, a temperature-entropy diagram has been prepared for the group of gases comprising O_2, N_2, CO (and therefore air) for a temperature range from 500 deg. fahr. abs. to 5500 deg. fahr. abs.

This permits the ready solution of problems dealing with these gases where high temperatures are involved without the necessity of employing the involved or indirect mathematical solutions that take account of the variability of the specific heats.

Examples are given of its use in the solution of problems in adiabatic compression and internal-combustion-engine ideal cycles.

BECAUSE of the added complexity that comes into the ordinary thermodynamic problems when the substance under consideration behaves as a vapor instead of a perfect gas temperature-entropy diagrams have found much favor for the graphical solution of problems dealing with fluids that may undergo changes of state. For the so-called permanent gases, which we ordinarily encounter under conditions remote from their critical condition, the various equations for perfect gases serve for most engineering problems and are so simple that temperature-entropy diagrams for them render small assistance and are seldom drawn.

However, there are cases frequently met in engineering practice where the assumptions underlying the development of the perfect-gas relations differ too widely from the actual conditions for their use to give satisfactory results. Most noticeably is this true in cases involving high temperatures, as in internal-combustion engines where very high temperatures may result from high compression ratios and from the combustion of the fuel.

The perfect-gas equations assume conformity with the laws of Boyle and Gay-Lussac and further that the specific heats are independent of both pressure and temperature, and for actual gases none of these are strictly true. For the gases dealt with in this paper and for the range covered the author believes the error introduced in accepting the first two assumptions—conformity with Boyle's law and the specific heat being unaffected by variation of pressure—to be inappreciable, and the correction for the variation of the specific heat with temperature to be the item of major importance.

For actual gases the specific heats increase with the temperature and differently for each gas. With gases of similar molecular structure, however, it becomes possible by dealing with one "mol"[2] of the gas to formulate *one* equation for the specific heat that will hold for the several gases constituting that group. Using such an expression it is possible to compute points for constructing lines of constant volume and constant pressure for this group of gases on coördinate axes of temperature and entropy. We have then a temperature-entropy diagram that takes cognizance of the variation of specific heat and permits a ready picturization of processes and cycles and the graphical solution of problems that would otherwise require the use of cumbersome mathematical expressions. Such a diagram makes it easy to predict final condition after adiabatic or isothermal change and the final temperature after the liberation of a known quantity of heat at constant pressure or volume.[3]

The splendid work of Goodenough and Felbeck[4] in surveying the entire field of research dealing with specific heats of gases and compiling and condensing the results into one group of fourteen equations has given a summary of the best data available for the gases commonly met with in engineering work. For air, and the diatomic gases oxygen (O_2), nitrogen (N_2), and carbon monoxide (CO), they have proposed the following equations and these have been used in the preparation of this paper.

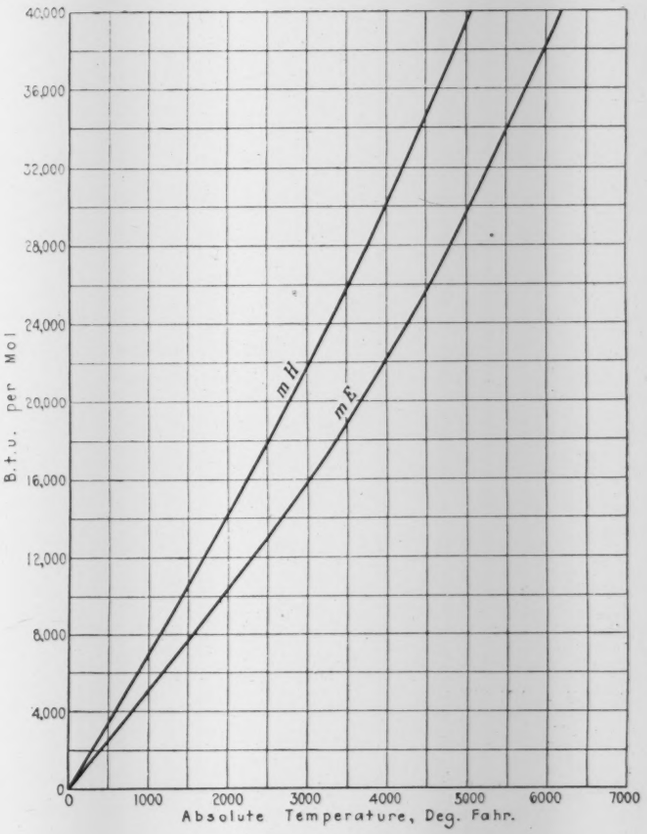

FIG. 1 CURVES OF mH AND mE FOR 1 MOL OF O_2, N_2, CO, AND AIR

$$mc_p = 6.93 + 0.1200 \times 10^{-6}\, T^2$$

$$mc_v = mc_p - 1.985$$

where c_p = instantaneous specific heat at constant pressure
c_v = instantaneous specific heat at constant volume
T = absolute temperature expressed in degrees fahrenheit
m = molecular weight of the gas. Therefore mc is the specific heat of one mol.

By *instantaneous* specific heat is meant the specific heat *at* any given temperature. If *mean* specific heat is desired for a range of temperatures from T_1 to T_2, it is given by the following relation:

$$c_{mean} = \frac{Q}{T_2 - T_1} = \frac{cdt}{T_2 - T_1}$$

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[1] Professor of Thermodynamics, Pennsylvania State College. Mem. A.S.M.E.

[2] A mol is a quantity of gas whose weight is equal to its molecular weight times the unit weight. Here, since English units are used, it is m pounds, where m is the molecular weight of the gas; i.e., a mol of oxygen is 32 lb. of oxygen.

[3] On the assumption of a single type equation satisfactorily representing the variation of specific heat with temperature, for all gases, Stodola in 1910 published a temperature-entropy diagram using metric units and 300 deg. cent. abs. for the origin of entropy. Adjustment of one of the coördinate axes was the means whereby the plot was made to conform to the different constants of the type equation when representing the different gases. Such a device is unnecessary if a diagram be drawn for each gas or group of gases that has a different specific-heat equation, as is done here for the air group.

[4] An investigation of the Maximum Temperatures and Pressures Attainable in the Combustion of Gaseous and Liquid Fuels, Bulletin 139, University of Illinois Engineering Experiment Station.

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The intermediate steps leading to the plotting of the final diagram may be briefly summarized as follows:

1 The computation of values for the instantaneous specific heats for a series of temperatures.

2 Dividing each of these by its temperature to obtain the entropy function c/T to be used in the expression[5]

$$d\phi = \frac{dQ}{T} = \frac{mcdt}{T} = \frac{mc}{T}\,dt$$

3 Substitution of the proper value for c in the above and its integration. The result is the increase of entropy for the change specified, i.e., at constant pressure or at constant volume, measured from whatever temperature has been selected as the origin for entropy measurements. For this diagram 500 deg. fahr. abs. (approx. 40 deg. fahr.) was chosen.

4 The orientation of the above curve on the temperature-entropy coördinates by assigning to it a definite pressure (or volume) as a starting point for laying off the similar curves for other pressures (or volumes). The pressure value used was 1024 lb. per sq. in.

5 From the origin as specified above the other curves were laid off by computing the entropy change for an isothermal compression or expansion to the condition desired.

6 While not strictly a part of the diagram, the values of the heat contents and intrinsic energy for changes along constant-pressure and constant-volume curves, respectively, were obtained by integrating the basic equation for specific heat given above between the limits of absolute zero and successive temperatures. These results and also the values of the *mean* specific heats are given in Table 1.[6] The completed temperature-entropy diagram is reproduced in Fig. 2.

TABLE 1 THERMAL PROPERTIES OF O_2, N_2, AND CO
(Values in B.t.u. per mol of gas[5])

Temp., deg. fahr. abs.	mc_p	Intrinsic energy, mE	Heat content, mH	Mean mc_v	Mean mc_p
500	6.96	2478	3471	4.956	6.942
1000	7.05	4985	6970	4.985	6.970
1500	7.20	7553	10531	5.035	7.021
2000	7.41	10211	14181	5.106	7.091
2500	7.68	12988	17795	5.198	7.178
3000	8.01	15914	21869	5.305	7.290
3500	8.40	19022	25970	5.429	7.420
4000	8.85	22339	30279	5.585	7.570
4500	9.36	25897	34830	5.758	7.740
5000	9.93	29725	39650	5.945	7.930
5500	10.55	33853	44771	6.158	8.140
6000	11.25	38310	52553	6.385	8.759

TABLE 2 ENTROPY INCREASE TO VARIOUS TEMPERATURES

T	$\frac{T}{500}$	$\log_e \frac{T}{500}$	$6.93 \times \log_e \frac{T}{500}$	$4.945 \times \log_e \frac{T}{500}$	$0.06 \times 10^{-6} \times (T^2 - 500^2)$	ϕ_p	ϕ_v
500	1.0	0.0	0.0	0.0	0.0	0.0	0.0
750	1.5	0.4055	2.810	2.005	0.019	2.83	2.02
1000	2.0	0.6931	4.80	3.425	0.045	4.85	3.47
1500	3.0	1.0986	7.62	5.435	0.120	7.74	5.56
2000	4.0	1.3863	9.61	6.850	0.225	9.84	7.08
2500	5.0	1.6094	11.15	7.955	0.360	11.51	8.32
3000	6.0	1.7918	12.41	8.860	0.525	12.94	9.39
3500	7.0	1.9459	13.48	9.620	0.720	14.20	10.34
4000	8.0	2.0794	14.40	10.28	0.945	15.35	11.23
4500	9.0	2.1972	15.22	10.86	1.200	16.42	12.06
5000	10.0	2.2026	15.95	11.38	1.485	17.44	12.87
5500	11.0	2.3979	16.61	11.85	1.795	18.41	13.65
6000	12.0	2.4849	17.24	12.28	2.145	19.39	14.43

COMPUTATIONS

The values of the various integrations performed in obtaining the final curves may be obtained directly and as a continuous plot if a mechanical integraph is available, or, as was done here, they may be obtained by repeated integration of the mathematical expression between progressively increasing superior limits. Below are given in summarized form those used in preparing the present paper.

Integration of Equation for Heat Content (H)

$$\int dH = \int c_p dt$$

but $$mc_p = 6.93 + 0.1200 \times 10^{-6}T^2$$

$$\therefore mH = 6.93T + 0.0400 \times 10^{-6}T^3$$

Integration of Equation for Intrinsic Energy (E)

$$\int dE = \int c_v dt$$

but $$mc_v = mc_p - 1.985$$

$$\therefore mE = mH - 1.985T$$

Computation for Entropy Change at Constant Temperature

For isothermal change, $PV = C$, and the work done is

$$ {}_1W_2 = P_1V_1 \log_e \frac{V_2}{V_1}$$

$$= RT \log_e \frac{V_2}{V_1}$$

$$= RT \log_e \frac{P_1}{P_2}$$

The general equation for the effect of adding the heat dQ is

$$dQ = dE + \frac{dW}{J}$$

and $$ {}_1Q_2 = \int c_v dt + \frac{{}_1W_2}{J}$$

Since $dt = 0$, $$ {}_1Q_2 = \frac{RT}{J} \log_e \frac{P_1}{P_2}$$

and the change of entropy (ϕ), $$ {}_1\phi_2 = \frac{{}_1Q_2}{T} = \frac{R}{J} \log_e \frac{P_1}{P_2}$$

$$= (c_p - c_v) \log_e \frac{P_1}{P_2}$$

For one mol, $$m\,{}_1\phi_2 = 1.985 \log_e \frac{P_1}{P_2}$$

and for a compression where $P_1/P_2 = 2$,

$$m\,{}_1\phi_2 = -1.3758$$

This is the increment or decrement of entropy at any temperature for an isothermal change of $P_1/P_2 = 2$, also for $V_2/V_1 = 2$.

Computation of Increase of Entropy above 500 Deg. Fahr. Abs.

$$d\phi_p = \frac{c_p dt}{T} = \frac{(6.93 + 0.12 \times 10^{-6}T^2)dt}{T}$$

From 500 deg.,

$$m\phi_p = \int_{500°}^{T} \left(\frac{6.93}{T} + 0.12 \times 10^{-6}T\right)dt$$

$$= 6.93 \log_e \frac{T}{500} + 0.06 \times 10^{-6}\,(T^2 - 500^2)$$

Similarly for the increase of entropy at constant volume, since $mc_p - mc_v = 1.985$,

$$m\phi_v = 4.95 \log_e \frac{T}{500} + 0.06 \times 10^{-6}\,(T^2 - 500^2)$$

The entropy increase to various temperatures is given in the last two columns of Table 2; the remainder of the table consisting of the values of the quantities used in calculating those columns.

Computation for Evaluating Pressure and Volume of Initial-Temperature Curves

Since 500 deg. fahr. abs. was taken as the zero of entropy it was also necessary to accept some pressure for a starting point, and 1024 lb. per sq. in. was taken for P_0, and to correspond with this V_0 was determined from the characteristic equation.

$$T_0 = 500 \text{ deg. fahr. abs.}$$

$$P_0 = 1024 \text{ lb. per sq. in.}$$

$$V_0 = \frac{1544 \times 500}{1024 \times 144} = 5.23 \text{ cu. ft.}$$

[5] Details of this computation are given later in connection with Table 2.

[6] A more complete tabulation of the values of mE (at 50 deg. intervals) is given in the Bulletin 139 referred to in footnote No. 4. A small graph of mE and mH is given in Fig. 1.

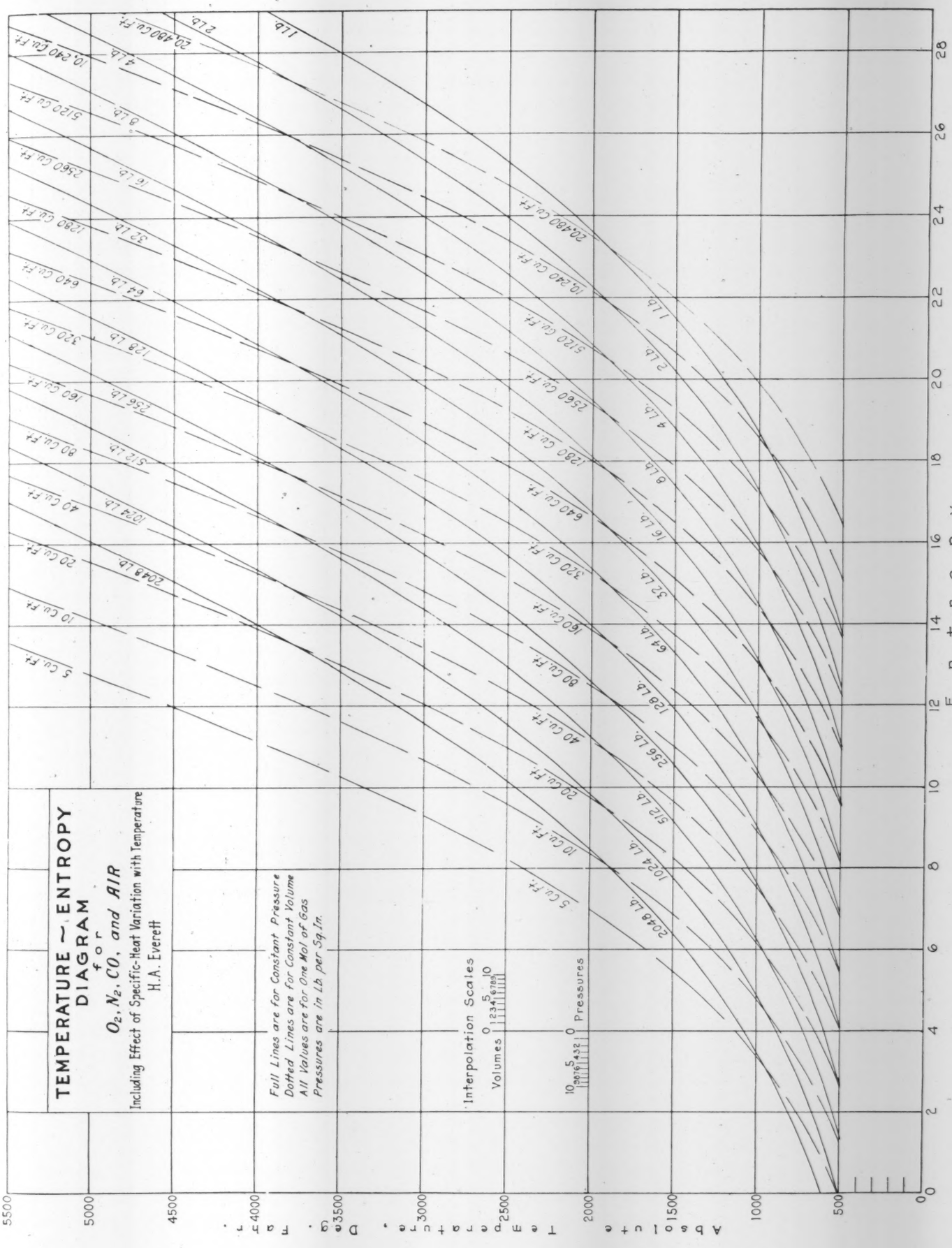

FIG. 2 TEMPERATURE-ENTROPY DIAGRAM FOR O_2, N_2, CO, AND AIR
(Including effect of specific-heat variation with temperature.)

To get the 10-cu. ft. curve the entropy increase from 5.23 to 10.22 at 500 deg. will be

$$\Delta\phi_t = 1.985 \log_e \frac{10}{5.23}$$

$$= 1.985 \times 0.6841$$

$$= 1.287$$

This quantity when added to the last column of Table 2 gives the abscissas for the 10-cu.-ft. curve as follows:

T	$\Delta\phi_s$	T	$\Delta\phi_s$
590	1.29	3500	11.63
750	3.31	4000	12.52
1000	4.76	4500	13.35
1500	6.85	5000	14.16
2000	8.37	5500	14.94
2500	9.61	6000	15.72
3000	10.68		

USE OF INTERPOLATION SCALES

Since the entropy change for isothermal action is a logarithmic function, equal spacing of the curves can only be obtained for specific values changing in a similar manner. The values of the successive curves are in the ratio of 2 to 1, but the interpolation for intermediate values is not proportional to the spacing and scales have been drawn at the left of the diagram, Fig. 2, to facilitate interpolation.

For example, if we wish to locate the curve for 90 lb. on the diagram, this lies between the 64-lb. curve and the 128-lb. curve, the interval between being 64 lb. Since 90 lb. is 26 lb. in excess of 64 lb., the 90-lb. curve will cross the lines of constant temperature $^{26}/_{64}$ or 0.41 of the interval to the *left* of the 64-lb. curve. Using the pressure interpolation scale, measure 0.41 and lay off this distance *along the lines of constant temperature* for a series of points on the 90-lb. curve.

Conversely, to find the value of any point lying between two curves, measure the distance to the next smaller curve, read this interval as a decimal from the proper interpolation scale, and multiply the value of the small curve by one plus the interpolated decimal. For example, a point lying between the volume curves of 80 and 160 cu. ft., scales from the volume-interpolation-curve scales 0.35 (measured from 80 toward 160 cu. ft.). Multiplying 80 by 1.35 gives 108 cu. ft., which is the interpolated volume.

USE OF THE DIAGRAM FOR THE SOLUTION OF PROBLEMS

I—Let it be required to find the final pressure resulting from the adiabatic compression of nitrogen from an initial pressure of 8 lb. per sq. in. and a temperature of 500 deg. fahr. abs. to a final temperature of 2500 deg. fahr. abs.

The solution by direct computation is as follows:[7]

$$a \log_e \frac{2500}{500} + b(2500 - 500) + \frac{c}{2}(2500^2 - 500^2) = \frac{R}{J} \log_e \frac{P_2}{P_1}$$

where a, b, and c are the constants in the equation for the specific heat at constant pressure and are 6.93, 0, and 0.1200×10^{-6}, respectively. Substituting,

$$6.930 \log_e 5 + 0 + \frac{0.1200}{2}(2500^2 - 500^2) \times 10^{-6} = 1.985 \log_e \frac{P_2}{P_1}$$

or $$11.51314 = 1.985 \log_e \frac{P_2}{P_1}$$

whence $$P_2 = 2642 \text{ lb. per sq. in.}$$

From the chart, Fig. 2, entering at 8 lb. per sq. in. and 500 deg., go vertically upward to the 2500-deg. line, where the final pressure is read by interpolation as 2640 lb. per sq. in.

II—Similarly, for a mol of oxygen compressed adiabatically from $P_1 = 4$ lb. per sq. in. and $T_1 = 1500$ deg. fahr. abs., to $T_2 = 5000$ deg., the final pressure will be

$$6.93 \log_e \frac{5000}{1000} + 0 + \frac{0.12 \times 10^{-6}}{2}(5000^2 - 1500^2) = 1.985 \log_e \frac{P_2}{P_1}$$

[7] Principles of Thermodynamics, by Goodenough, p. 279.

whence

$$\log \frac{P_2}{P_1} = 4.880$$

and

$$P_2 = 4 \times 131.7 = 527$$

From the diagram, entering at $P_1 = 4$ lb. and $T_1 = 1500$ deg. a vertical line to 5000 deg. temperature gives the pressure of 530 lb. per sq. in.

III—Plot and find the thermal efficiency of an ideal Otto-cycle engine with compression ratio of 5, when the heat liberated per mol of charge is 23,450 B.t.u. If the charge be considered to behave as air (or O_2, N_2, or CO) and initial conditions be assumed, the various events of the cycle can be plotted on the temperature-entropy diagram and the ratio of the net to the gross areas is equal to the thermal efficiency.

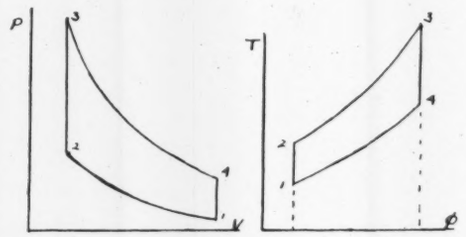

FIG. 3

The following have been taken for initial conditions: $P_1 = 8.46$ lb. per sq. in., $T_1 = 779$ deg. fahr. abs., $V_1 = 990$ cu. ft. (per mol). The condition at the end of the compression stroke will be (adiabatic compression from 990 cu. ft. to 990/5 cu. ft.) $P_2 = 77.6$ lb. and $T_2 = 1440$ deg. From point 2 the liberation of 23,450 B.t.u. at constant volume will give $T_3 = 5100$ deg. and $P_3 = 276$ lb. From point 3 adiabatic expansion to the initial volume (990 cu. ft.) gives the point 4 with $P_4 = 33.6$ lb. and $T_4 = 3200$ deg. The efficiency of this cycle is found by taking the ratio of the area enclosed by the figure 1,2,3,4 to the area of the figure lying between the curve 2,3 and the base line. This works out to be 42.6 per cent.

The above *initial* data were taken from one of a series of tests (test No. 22) made by Rosecrans and Felbeck on an actual gas engine. These tests were made with great refinement and were reported in Bulletin 150 of the University of Illinois Engineering Experiment Station issued last year. For this test the ideal efficiency, taking cognizance of variations in the specific heats *and also the variations in the chemical characteristics*, is computed as 36.1 per cent. The difference is probably attributable to the divergence of the chemical characteristics of the actual charge from those of the gases for which the diagram is prepared.

As a matter of collateral interest there is given in Table 3 a comparison of the cycle points and efficiency as obtained by three

TABLE 3 COMPARISON OF CYCLE POINTS AND EFFICIENCY AS OBTAINED BY VARIOUS ASSUMPTIONS

		From $T-\phi$ diagram	As computed[1]	Air standard
Point 1—At beginning of adiabatic compression	P_1	8.46	8.46	8.46
	V_1	990	990	990
	T_1	779	779	779
Point 2—At end of adiabatic compression	P_2	77.6	75.9	80.6
	V_2	198	198	198
	T_2	1440	1400	1486
Point 3—At end of complete combustion	P_3	276	245.3	337.5
	V_3	198	207	198
	T_3	5100	4722	6231
Point 4—After adiabatic expansion (5 to 1 volumes)	P_4	33.6	33.2	35.4
	V_4	990	1033	990
	T_4	3200	3199	3266
Cycle efficiency, per cent		42.6	37.1	47.5

[1] By Rosecrans and Felbeck, Test 22.

assumptions; first, that the charge behaves like the gases for which the diagram is made; second, that the actual properties are dealt with throughout as computed by Rosecrans and Felbeck; and third, that the charge conforms to the assumptions of the Air Standard, i.e., the same properties as air and constant specific heats.

The Guarded-Plate-Heater Method of Testing Low-Temperature Insulators Compared with Several Box Methods

By E. F. GRUNDHOFER,[1] STATE COLLEGE, PA.

THE interest in the comparative insulating qualities of building materials is shown by the number of investigators who are seeking information in this field. Many investigations have been carried out and many values have been submitted, but when one attempts to make comparisons of the data secured, one is immediately impressed with the apparent lack of uniformity in methods and conditions of testing, and the probability of useless duplication of effort. There has been no recognized standard method, and the wide variety of methods used and the differences in conditions of testing have made it practically impossible to compare values obtained by the various experimenters.

After having conducted tests with several apparatus and having found many shortcomings in the various methods, the Engineering Experiment Station of The Pennsylvania State College decided that the important phase of the work was the development of a method of testing that would be reliable and that could be standardized.

The first test apparatus used here was a large cubical box made of the material to be tested. Its limitations were soon discovered and it was replaced by a test box recommended by the United States Postal Department for use in testing materials to be used in mail cars. A careful investigation of this box showed many faults and it was followed by a cubical-heater test box upon which the material to be tested was fastened. This method also had its faults and led finally to the design and adoption of a guarded plate heater which was used in conjunction with a constant temperature room although it is now being used under various conditions in connection with some newly developed heat meters.

Types of Test Apparatus Employed

The Cubical Test Box (Fig. 1) is a 5-ft. hollow cube made up of 3-in. corkboard. One side is removable to permit the substitution of other material to be tested.

Heat was supplied to the test box by an electric coil. The coil was covered with asbestos paper to prevent excessive radiation. A small electric fan was used to circulate the air inside the test box.

The Post Office Department Test Box (Fig. 2) was built according to the specifications of the Post Office Department except that it was made 16 in. wide instead of 13 in. in order to accommodate thicker test blanks. It was built of kiln-dried white pine 32 × 32 × 16 in. outside dimensions. Its walls are 4 in. thick and are made up of five layers of wool felt which are contained between faces of $^1/_2$-in. pine boards. The box has removable blanks, 2 ft. square, for which similar-sized blanks of the material to be tested are substituted. The heating element is a coil made of 14 ft. of 0.057-in. diameter manganin wire. It is located in the center of the box and about four inches from the bottom. A very small electric fan is placed inside the box for circulating the air.

The Cubical-Heater Test Box (Fig. 3). The heating element of this test box is a hollow cube around which is built a box of the material to be tested. The heating element is a 14-in. hollow cube, made of $^1/_4$-in. asbestos boards. Its six faces are laced with 31.25 ft. of manganin resistance wire which is equally distributed over the six faces, but so arranged on each vertical face that there is slightly more wire below the center than above. This cube is encased in a 16-in. box of galvanized iron which is intended to diffuse the flow of heat to the test material. The space between the cubes is divided into separate airtight compartments on the vertical faces by the use of two horizontal baffles which divide the face into three equal spaces. The effect of these compartments and the method of wiring tend to equalize the temperatures of the heater. A wooden frame is constructed on this heating element, and upon this frame is built a cube of the material to be tested.

The Guarded Plate Heater is a flat plate (Figs. 4, 5, and 6) 36 × 36 × $^1/_2$ in. thick. It consists of two separate elements, the main heater and an auxiliary element which prevents edge losses from the main heater. The main heating element is made up on a 30-in. square and consists of 210.62 ft. of advance resistance ribbon, 138.57 ft. of which furnishes heat to the 2-ft.-square testing area. The edge heater is a square annulus which fits around the heater and leaves a clearance of about $^1/_8$ in. Its outside dimensions are 36 in. square. It also is wound with advance resistance ribbon, which is an independent heating circuit. Both faces of the heating element are insulated with thin sheets of micanite. Copper plates are fastened against these, and bolted together through the element by the use of flat-headed bolts which are countersunk and tapped in the copper plates. The copper plates are in the same form as the asbestos element, that is, in two separate sections. The copper squares are 2 ft. on each side and have a clearance of $^1/_8$ in. from the copper annulus. The breaks in the two elements do not coincide. The resistance ribbon crosses the break in the copper plate and will prevent a temperature drop at that point on the copper element, while the copper annulus will act as a diffuser at the break between the two heating elements. The main heater has a total resistance of 14.802 ohms and will take a current of 7.43 amperes when connected directly to a 110-volt circuit. However, the maximum voltage of the storage battery is 60, so that the heater will not need to carry more than 4.05 amperes under test conditions.

Resistance thermometers in connection with a Wheatstone bridge were used for temperature measurements with the three box methods. Flat nickel spirals enclosed in nickel-plated cylindrical tubes were used for other temperature measurements. With the guarded-plate-heater method, copper-constantan thermocouples and a potentiometer were used for measuring temperatures.

The heat input to the various test boxes was measured by the voltmeter-ammeter method. Humidity of the test room was measured by a wet-and-dry-bulb thermometer.

Results Shown by Analysis of Tests

Cubical Test Box. The conduction values for the series of tests on the 5-ft. cubical test box show an increase of 10.65 per cent for an increase of 20 deg. fahr. in mean temperature, or an increase of 0.503 per cent per degree from a mean temperature of 49.6 deg. fahr. to one of 69.6 deg. fahr. This is probably due in part to heat leakage through joints, which is borne out by a comparison of the conduction values themselves since they are somewhat higher than is expected for this material.

An analysis of the tests brings out several pertinent facts. One of the most important points is the apparent inability to control the room temperature closely enough. This, no doubt was due to the large size of the room,[2] which made the temperature adjustment too slow and permitted appreciable temperature gradients to obtain. The method of controlling the temperature, by changing the speed of the brine-circulating pump, also left much to be desired since it depended very much on the skill of the operator in manipulating the pump whether or not an acceptable test could be obtained.

While the use of resistance thermometers for measuring air tem-

[1] Pennsylvania State College.

For presentation at the Annual Meeting, New York, December 6 to 9, 1926, of The American Society of Mechanical Engineers, at a joint session with the American Society of Refrigerating Engineers. Program arranged by the Committee on Heat Transmission, National Research Council.

[2] At this time the thermal plant did not contain the small improved calorimeter room.

Be sure to bring this copy with you to the Annual Meeting

peratures may be satisfactory, they are not adapted to the measurement of surface temperatures. Because of their bulk it is impossible to record a true surface temperature, which should be taken just under the surface in order to prevent the effects of convection and radiation. Hence it is far preferable to use thermocouples, which can be placed just under the surface of the material.

If a box like this is to be used at all it should be for comparative values only.

Postal Department Test Box. The tests on this box show that the increase in conduction with mean temperature is quite rapid, showing an increase of 69.1 per cent for a rise in mean temperature from 52.57 deg. fahr. to 84.42 deg. fahr. This is an increase of 2.17 per cent per degree, which is undoubtedly more than should be expected for this corkboard, and may be attributed largely to two factors: leakage and the agitation of the air inside the box.

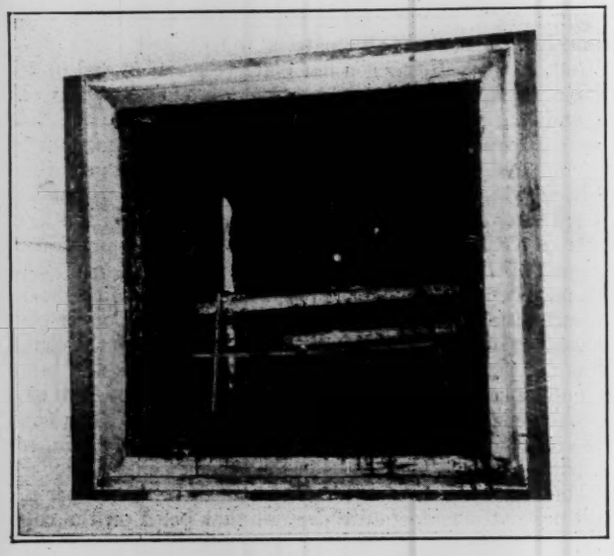

FIG. 1 CUBICAL TEST BOX

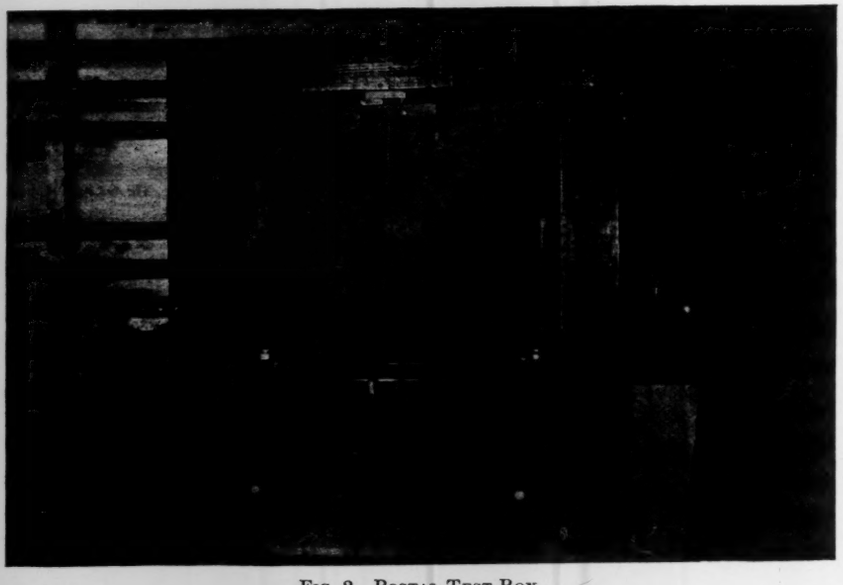

FIG. 2 POSTAL TEST BOX

From an analysis of the tests of this apparatus the most important conclusion is that it may be used for comparative testing only and should not be used for the determination of true values.

Test blanks should be used only in positions in which their exterior surfaces are flush with the outside surfaces of the box. The blanks should also be approximately the same thickness as the walls of the box, in order that the surfaces shall be subjected to approximately the same conditions.

A test box with overhanging sides should not be used because of the reduction of natural convection on the outside which is due to the pockets thus formed, and because of the difficulty involved in determining the true effective area and hence the true loss through the periphery.

The effects of the forced circulation of the air within the box and of the excessive radiation to the surface of the blanks when placed near the heating coil are errors which should be eliminated.

For the determination of conductivity, temperatures should be measured by thermocouples instead of resistance thermometers. The thermocouples should be placed at the centers on both surfaces of one of the vertical walls of the test box. Three or more couples should be used, either in series or separately. It will be found that a weighted average of the data obtained on all six faces will be practically equal to the data obtained on one of the vertical walls at its center.[3]

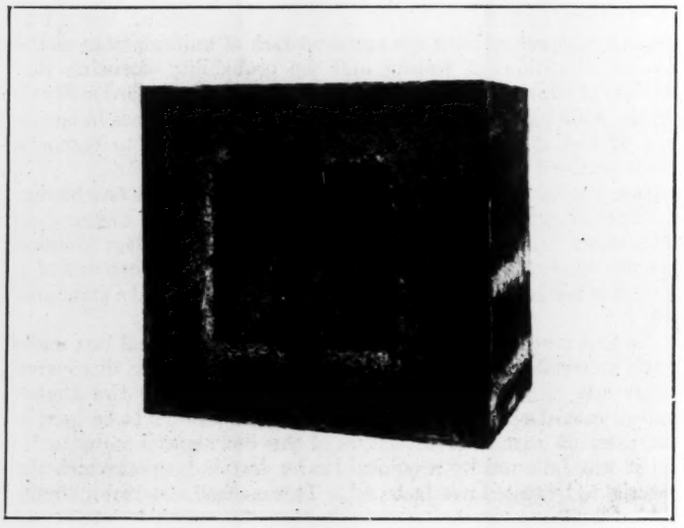

FIG. 3 CUBICAL HEATER TEST BOX OF CORKBOARD, SHOWING SECTION REMOVED FOR TESTING SOME OTHER MATERIAL THAN CORK

With the necessary temperatures observed as indicated in the preceding paragraph, it will not be necessary to approximate the temperatures on the periphery as was the case in this test method. In these tests, temperature measurements were taken with resistance thermometers on the inside and outside surfaces of the test blanks only.

The use of a sensitive hand-regulated brine valve is an improvement over the use of an automatic thermostat, since with any automatic equipment there will be a lag in the operation.

Cubical-Heater Test Box. The results obtained from this box show more acceptable values than those of either of the other two test boxes, in spite of its apparent defects. The values for corkboard secured from this test box showed an increase in conduction from 0.97 at a mean temperature of 55.61 deg. fahr. to a value of 0.1116 at a mean temperature of 88.51 deg. fahr. This is an increase of 15.05 per cent, or an increase of 0.458 per cent per degree fahrenheit.

While the data show higher temperatures on the top of the box and lower temperatures on the bottom than those on the vertical walls, it is of importance to note that the values obtained from data taken on one of the vertical walls are practically equal to the values obtained by using a weighted average of the data obtained on all six faces. For commercial testing this would obviate the necessity for placing couples on all faces, and so would require fewer observations to be made.

Although this test box gave more satisfactory values than either of the other two, several criticisms can be made against it. Only two baffles were used on each vertical face of the heater for the

[3] See Table 4, page 24, Bulletin No. 33, Engineering Experiment Station of The Pennsylvania State College, by E. F. Grundhofer.

purpose of lessening the convection currents, and they were only partially effective. The addition of two more baffles, on the top and bottom edges, would aid in cutting down the convection on the outside surface of the cube, but would not eliminate the error since no provision is made for preventing the convection of the heat which passes to the inside of the hollow heater. If the cube were filled with some material like granulated cork the convection on the

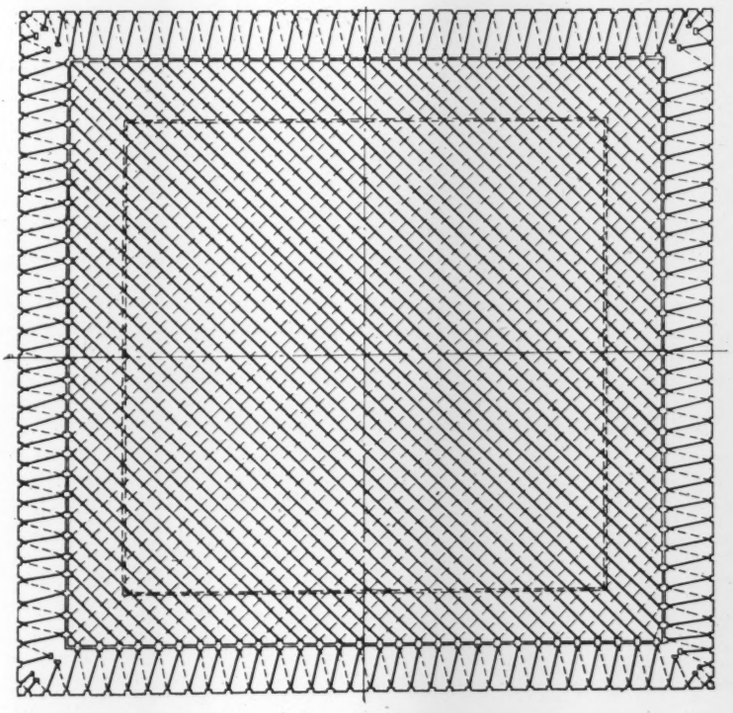

FIG. 4 WIRING DIAGRAM OF GUARDED PLATE HEATER, SHOWING METHOD OF LACING RESISTANCE WIRE ON MAIN HEATER AND ON ANNULUS

inside would be eliminated, no doubt, but because of the thermal capacity of the material it would require a considerable amount of time to determine when equilibrium had been reached. It would also be difficult to detect sudden variations in heat flow, if any should occur, due to the slowness with which a change would become evident. On the other hand, the material might act as a reservoir from which heat would flow to the material being tested and tend to hold its temperature more nearly constant, if for any reason there should be a temporary drop in the temperature of the heating coil. This would not be true, however, for temporary increases in the temperature of the heating coil, although the granulated cork would tend to absorb some of the excess heat. The use of several horizontal partitions within the heater might be acceptable, since they would undoubtedly cut down the convection, and still the air cells thus formed would not have so great a thermal capacity that the heat flow would be as sluggish as with the granulated cork.

Guarded Plate Heater. An examination of the conduction values for the corkboard blanks tested on the guarded plate heater shows a group of lower values than was obtained on any of the other test apparatus, and also shows a smaller increase in conduction with increase in mean temperature. It shows an increase from 0.093 B.t.u. at a mean temperature of 45.6 deg. fahr. to 0.1035 B.t.u. at a mean temperature of 98.39 deg. fahr. This is an increase of 11.3 per cent for an increase in mean temperature of 52.69 deg. fahr. or an increase of 0.214 per cent per degree in this temperature range.

A review of the guarded plate heater itself leaves little to be desired in revision, although for testing certain uniform materials a smaller-sized heater might be desirable on account of the weight and bulk of the larger size.

The use of thermocouples instead of resistance thermometers for measuring temperatures is a decided improvement, especially for determining surface temperatures, which cannot be accurately determined with the bulkier resistance thermometers.

It was found desirable to keep the apparatus heated overnight or between tests, because it required some time to heat up from the cold-room temperature for each test. This is particularly true in testing good insulating materials. It is also desirable to hold the temperature of the heater from a standpoint of moisture absorption in the material being tested. If the material were allowed to cool and stand idle for different lengths of time the amount of moisture absorbed would be variable, but with the heater kept at approximately the same temperature it is not only possible to secure temperature equilibrium more readily but also to secure more nearly constant moisture content of the material, assuming of course that the humidity of the room remains nearly constant.

In the use of a guarded plate heater in a cold room it is not advisable to attempt to test blanks of any considerable thickness. Although there is a balance of temperature and a rectilinear flow of heat guaranteed at the surface of the heater, there is no guarantee that this is true at some other plane. The thicker the material is, the greater is the tendency for the

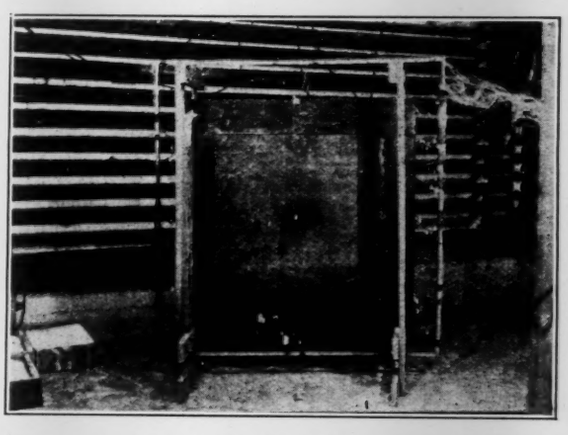

FIG. 5 GUARDED PLATE HEATER, SHOWING TEST AREA COPPER PLATE AND COPPER-PLATE ANNULUS

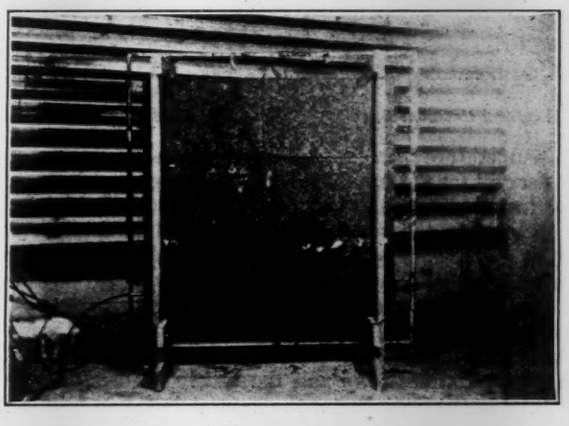

FIG. 6 GUARDED PLATE HEATER WITH CORKBOARD TEST BLANKS IN POSITION

heat to deviate from a rectilinear path. On materials of the thickness tested here there is slight reason to expect an appreciable error. If it is necessary or important to test materials of considerable thickness it could be done in all probability and with a fairly high degree of accuracy by using the guarded plate heater in connection with cooling plates, which are tanks containing crushed ice or running cold water. The tanks are placed against the outside faces of the test blanks and the entire apparatus is placed in a room which has its temperature held at the mean temperature of the material being tested. However, the use of cooling plates would prevent securing surface transmission.

With the hot-plate method, care must be taken to clamp the test blanks snugly against the heater plate in order that no air spaces may be formed, since their presence will affect the resistance to the

flow of heat. Care should also be taken that the clamps which hold the test material against the heater are not so bulky as to affect the heat flow.

SUMMARY

In comparing the methods employed at this Station for testing low-temperature insulating materials, the same kind of test material was used in each test method. Corkboard was chosen because it is probably the best-known material for low-temperature insulation and has been tested by most experimenters and its values are fairly well established. The corkboard blanks used for these tests were from the same shipment and were of the same density.

All of these tests were conducted under similar conditions, so that any variations in values of the materials may be attributed largely to the accuracy of the individual method of testing.

An examination of the values plotted in Fig. 7 shows in general the highest values of conduction for the postal test box, with the cubical test box, the cubical-heater test box, and the plate heater following in order. The increase in conduction per degree fahrenheit of mean temperature increase shows 2.17 per cent for the postal box, 0.593 per cent for the cubical test box, 0.458 per cent for the cubical-heater test box, and 0.214 per cent for the guarded plate heater.

TABLE 1 CONDUCTION VALUES FOR CORKBOARD AS OBTAINED WITH THE FOUR METHODS OF TESTING

Large cubical box		Postal test box		Cubical-heater box		Guarded plate heater	
t_m	c	t_m	c	t_m	c	t_m	c
49.6	0.122	52.57	0.111	56.21	0.0970	45.60	0.093
55.55	0.125	69.75	0.152	55.61	0.0971	60.39	0.095
67.25	0.132	84.42	0.186	73.17	0.1063	68.30	0.096
69.6	0.135	...	...	88.51	0.1116	81.54	0.102
...	...	...	...	...	...	91.70	0.103

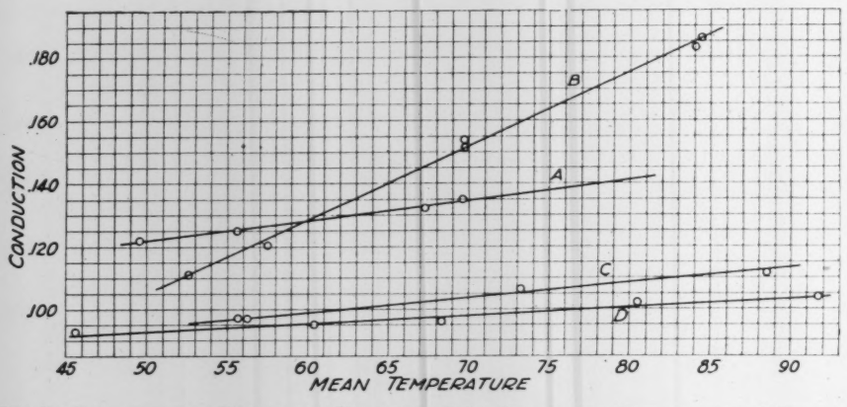

FIG. 7 COMPARISON OF CONDUCTION VALUES OF 3-IN. CORKBOARD TESTED ON THE SEVERAL TEST APPARATUS

(*A*, cubical test box; *B*, postal test box; *C*, cubical-heater test box; *D*, guarded plate heater.)

In comparing the several methods for their relative value in accuracy and reliability it must be remembered that there has been a similarity of plan and procedure. Temperature measurements were taken on both surfaces of the material under test, so that the temperature difference for any heat flow could be determined. The greatest obstacles to the ideal condition of heat flow in the box methods are corner effects and the leakage of heat through poor joints, and in the plate heater the natural deviation from a rectilinear path or edge loss which is due to imperfect "guarding."

The character of a material determines its gradient as indicated by its surface-temperature measurement for any given heat input, and any differentials indicated by the temperature measurements on the surfaces should indicate the amount of heat flow through the material. If there is no edge loss or other leakage the differential measurement will be a true indication of the heat flow as indicated by the voltmeter-ammeter method. However, if there were leakage the differential would indicate some amount of heat less than the amount measured by the voltmeter-ammeter method. Hence the maximum differential indication obtained would show the greatest accuracy in the measurement of heat flow, since it is impossible to indicate more heat than actually passes through the material for any given heat input, but due to leakage it is possible to assume a smaller differential to correspond to a greater amount of heat than actually passes through the material.

We may then assume the maximum differential for any given heat flow to be the nearest approach to ideal accuracy, which is a condition of no heat leakage. The largest temperature difference divided into the electrically measured heat input gives the smallest value for conduction of the material. Hence the lowest value for conduction obtained on the same material in the various methods should indicate the method of greatest accuracy.

While the values for conduction for any given heat input will be lower in methods where no leakage occurs, the mean temperature of the materials will be higher; and since it is quite probable that due to convection the relative resistances of the material and of any path of leakage.

In any method care should be taken to avoid any shape in which there is likely to be a deviation from the rectilinear flow of heat through the test specimen, since the shape factor may be difficult to calculate and in some cases practically impossible to determine.

In accordance with the foregoing discussion, and from an examination of the conduction values obtained from the various methods, we conclude that the Guarded Plate Heater is the best method employed here. From the same viewpoint we may rate the others in order as follows: Cubical-Heater Test Box, Cubical Test Box, and the Postal Department Test Box.

As may be inferred from the conclusions regarding the relative accuracy of the test methods employed here, this Station now uses the guarded-plate-heater method of testing insulating materials, and the values accepted by it as standard for the various insulating materials are those obtained by that method.

When a comparison is made of data on the insulating efficiences obtained by various apparatus at various places and perhaps at different temperatures, the errors made in such a comparison may be considerably greater than the actual difference in the insulating qualities of the materials compared. It is quite possible that the material for which the lower efficiency is obtained may possess the better insulating quality. Under existing conditions it seems as though the adoption of some method as a standard would not only be desirable but necessary.

If any recommendation were to be made for the adoption of a standard method for testing low-temperature insulating materials, the author would undoubtedly advocate the use of the guarded plate heater. This method not only seems to offer greater accuracy but is also adaptable to various conditions in testing. It may be used in connection with cooling plates of running water or crushed ice for the determination of conductivity, or in a so-called constant-temperature room, in which case surface transmission for one face may be obtained, as well as values for conductivity.

Since comparisons between the values of different insulating materials can be made only on the basis of their heat-transmitting powers, it is of the utmost importance that these values be obtained in such a way as to permit comparison.

Appendix

THERMAL CONDUCTIVITIES OF SEVERAL MATERIALS DETERMINED BY THE PLATE-HEATER METHOD

	Density, lb. per cu. ft.	Mean temperature of material, deg. fahr.	Thermal conductivity c
Balsa wood	9	72	0.3663
Corkboard (nonpareil)	9	46	0.279
	9	60	0.2858
	9	68	0.2876
	9	82	0.306
	9	92	0.3105
Corkplate, compressed (nonpareil)	28.5	80	0.507
Corkboard (rubberized)	11.86	66	0.2556
	11.86	85	0.2854
Ebony asbestos	132.0	80	3.337
Fibrofelt	18.84	76	0.3178
	18.84	109	0.3318
Flaxlinum	17.52	63	0.2876
	17.52	86	0.3046
Lithboard	15.29	55	0.3776

Methods That Have Been and Are Being Used for Measuring Heat Transmission

A Review of the More Important Methods That Have Been Used for Measuring Heat Transmission for Building and Insulating Materials, and a Discussion of Their Sources of Error and Probable Accuracy

By F. G. HECHLER,[1] STATE COLLEGE, PA.

ENGINEERS and others who are interested in the thermal properties of building and insulating materials are often at a loss to know which of the available data for a given material are the most trustworthy. For most of the usual materials used for building and insulation the heat-insulating values have been determined by several investigators. Unfortunately, there is often a serious lack of agreement in the thermal values of materials which apparently are similar. However, in many cases the descriptions of the test method and of the material tested are so meager and their physical characteristics are so poorly defined that it is impossible to definitely reproduce either the material or the method by which it was tested. Many investigators do not appear to have appreciated the importance of specifying such properties as specific weight, mean temperature of test, moisture content, etc., with the result that we have a bewildering mass of data difficult to interpret.

Results are also complicated by the variety of test methods used by different workers. Some of the methods employed are subject to serious errors and even under favorable circumstances yield results which are of comparative rather than of absolute value. In some methods the results are influenced by the surrounding objects, as well as by the position and location of the test specimen, and, finally, it is frequently not clear whether the results represent conductivity or transmittance, or something in between the two.

The object of this report is to review the more important methods that have been used for measuring heat transmission for building and insulating materials, and to discuss the sources of error and the probable accuracy of the various methods. The term "heat transmission" will be used in the restricted sense of transmittance, thus excluding a consideration of those methods that are adapted primarily for determining conductivities. It is to be noted, however, that the methods used for determining transmittance may also be used for measuring conductivities.

Definitions

When heat flows from one medium to another, through one or more intermediate resistances, the rate of heat flow per unit area divided by the difference in temperature of the two media is defined as the *transmittance*, and will be designated by the symbol U.

$$U = \frac{H}{t_1 - t_2}$$

where H = rate of heat flow per unit area in B.t.u.
t_1 = temperature of the warmer medium, deg. fahr.
t_2 = temperature of the colder medium, deg. fahr.

When defined in this way transmittance is the equivalent of "overall coefficients," such as the commonly used "coefficient of heat transmission from air to air." The value of the transmittance depends not only on the thermal resistance of the material, but also on the film resistances at its surfaces. The latter are largely influenced by position, nature of surroundings, character of surface, moisture, and air movement. Therefore transmittance is an unsatisfactory unit for recording and reporting results of heat-transmission tests, however useful it may be for comparative purposes in particular cases.

When dealing with compound walls, the effect of the variable surface resistances may be eliminated by expressing the result as the *conductance* (C), which is defined as the rate of heat flow per unit area divided by the difference in temperature of the two surfaces.

$$C = \frac{H}{\Delta t}$$

where H = rate of heat flow per unit area in B.t.u.
Δt = temperature difference of the two surfaces, deg. fahr.

For a homogeneous material, conductance is replaced by the conductivity (k), which is the rate of heat flow per unit area divided by the unit temperature gradient between the two surfaces of the material.

$$k = \frac{H}{\Delta t / \Delta x}$$

where H = rate of heat flow per unit area in B.t.u.
Δt = temperature difference of the two surfaces, deg. fahr.
Δx = thickness of material, inches
$\Delta t / \Delta x$ = unit temperature gradient.

Transmittance and conductance differ only in the points between which the temperature difference is measured. Investigators have not always kept this in mind and have sometimes neglected to state what temperatures were used in computing their results. It is not improbable that in some cases values reported as conductivities have been computed from temperature differences from "air to air" rather than from surface to surface, and in some instances there is reason for believing that the temperature difference used is that between the surface on one side and the air on the other. This lack of care in determining the temperature gradient undoubtedly accounts for some of the discrepancies in the published values.

Methods Used for Measuring Transmittance

The principal methods that have been used for making heat-transmittance tests of building and insulating materials may be classified as follows:

1 Ice-box
2 Oil-box
3 Cold-air-box
4 Hot-air-box
5 Guarded hot-air box
6 Steam or condensation.

The details of the set-up with each of these methods may be varied to suit the needs and ideas of the individual investigator. Such modifications result in more or less refinement which may or may not improve the probable accuracy of the results.

The essential features of the different methods will be briefly described.

The Ice-Box Method

This is probably the simplest of the various methods and is shown in Fig. 1. A metal box, or cube, covered on the outside with the material to be tested is filled with ice. The temperature within the chamber is usually assumed to be 32 deg. fahr., and this is generally taken also as the inside surface temperature of the material under test. Thermometers are usually used to determine the temperature of the outer surface, or of the surrounding air. The heat

[1] Professor of Engineering Research, Pennsylvania State College, Assoc-Mem. A.S.M.E.

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transmitted is determined from the rate at which the ice melts. When used as indicated this method does not give transmittance; if the temperature gradient between the two surfaces is used the result will be the conductivity; if the outer air and the inner surface temperatures are used, the result is an indefinite, undefined unit.

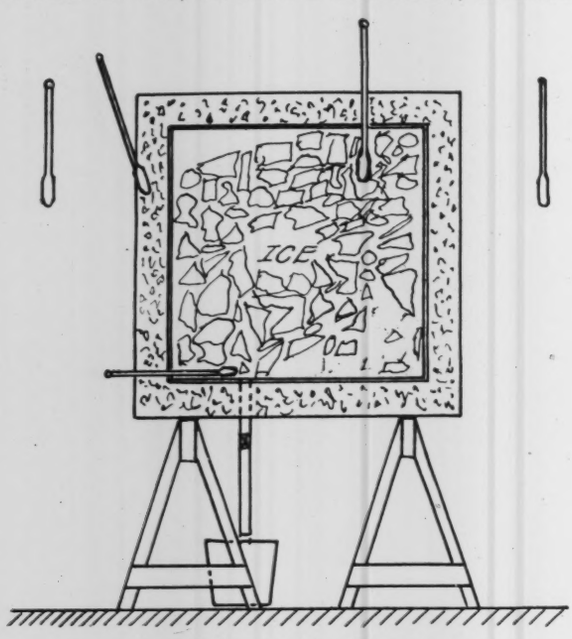

FIG. 1 THE ICE-BOX METHOD

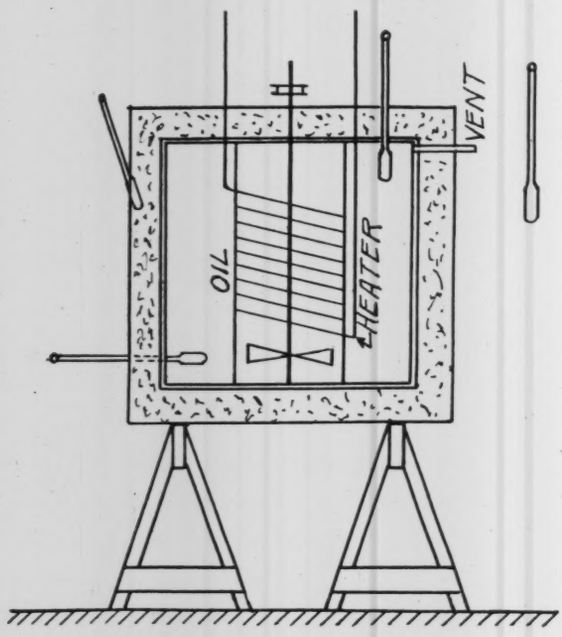

FIG. 2 THE OIL-BOX METHOD

This method may be unsatisfactory in the following respects:

1 It is difficult to keep the entire box at 32 deg. fahr.; the top of the box is liable to be at a somewhat higher temperature.

2 The box must be opened from time to time to replenish the ice, at the same time part of the water formed by the melting of the ice must be drawn off. The thermal-equilibrium conditions of the box are disturbed by this operation so that the continuity of the test is destroyed.

3 To keep the box filled, the water from the melting ice must be retained; hence there is no way of frequently determining the rate of melting to find whether or not it is uniform throughout the test.

4 The temperature drop through the wall of the metal box affects the temperature gradient through the material under test.

5 The available temperature range is limited by the temperature of the outside air, which must be kept constant, if accuracy is desired. For example, if the room temperature is 72 deg. fahr., a variation of one degree would result in a variation of 2.5 per cent in the temperature gradient, which should have a similar effect on the rate of melting.

THE OIL-BOX METHOD

This method is shown in Fig. 2. A metal box, or cube, covered with the material to be tested is filled with oil which is kept at the desired temperature by an electrical heater immersed in the oil. A mechanical stirrer is used to insure uniform temperatures throughout the oil. The heat transmitted is determined from the electrical input to the heating coil and the heat equivalent of the work of the stirring device.

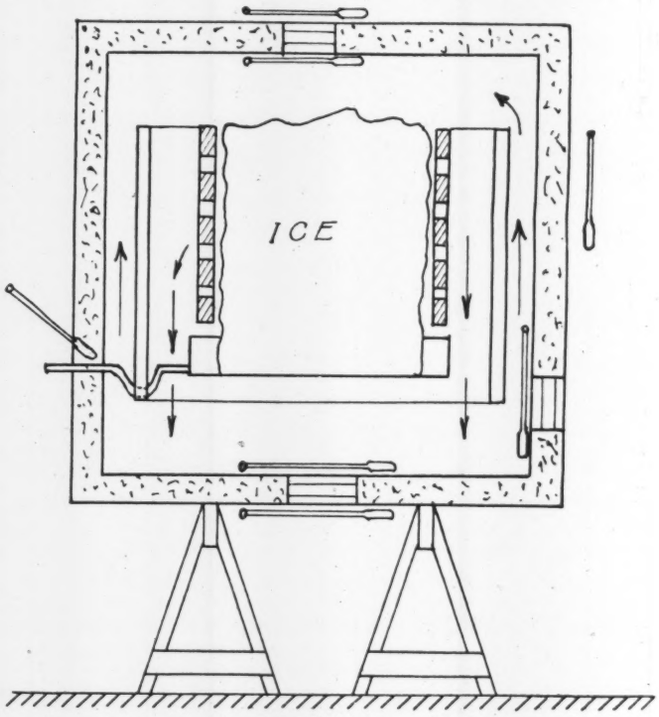

FIG. 3 THE COLD-AIR-BOX METHOD

The results of this method, when used as indicated in Fig. 2, are similar to those of the ice box and do not represent the transmittance. The possible temperature range is greater than for the ice-box method. In this case the room temperature fixes the minimum point.

There is no assurance that the temperature at the top of the box will be the same as the rest of the box; it is difficult to make the proper correction for the heat due to the stirrer; the oil circulation may short-circuit, resulting in unequal temperatures throughout the oil; also it is difficult to determine the heat loss (*a*) through the stirrer rod, (*b*) through evaporation of oil, and (*c*) by conduction through the overflow pipe.

THE COLD-AIR-BOX METHOD

This method, illustrated in Fig. 3, is similar to the ice-box method except that an open air space is provided between the ice container and the test material which permits the determination of the transmittance from observation of the temperatures of the air inside and outside of the box. The heat flow is determined from the rate of melting of the ice. The water due to the melting is drawn off regularly, and need not be retained in the box as in the ice-box method; this furnishes a check on the uniformity of the rate of melting of the ice. In this connection, Bost,[2] using identical uninsulated

[2] W. D. A. Bost, Methods and Apparatus for Ascertaining the Heat Conductivities of Insulating Materials. Trans. First Int. Congress of Refrig., Paris, 1908, vol. 2, pp. 487–513.

tin cubes filled with ice and placed in a room, found variations in the rate of melting of the ice as high as 30 per cent, from which he concluded that the method was not reliable. On the other hand, Biquard[3] found that if transparent ice in large prismatic blocks is used less than 0.3 per cent of water adheres to the ice, while if crushed ice is used as much as 7 per cent of water may adhere to the ice.

The ice container is usually placed near the top of the chamber and natural circulation of the air is depended on to give a uniform temperature throughout the box; actually, uniformity of temperatures will never be attained; the top of the box will be warmer than the bottom, and parts of the box will be "pocketed" due to short-circuiting of the air currents. The box must be made so that it can be opened in order to replenish the ice from time to time, thus destroying the thermal equilibrium of the test. The temperature range is limited in this method by the temperature of the room in which the test is made.

THE HOT-AIR-BOX METHOD

The arrangement of the hot-air-box method is shown in its simplest form in Fig. 4. The box is constructed wholly of the material to be tested, using only such light wooden supports as may be necessary to give it structural strength. The heat supplied to the box is measured electrically, and a small electric fan is frequently used to circulate the air in the box in an endeavor to make

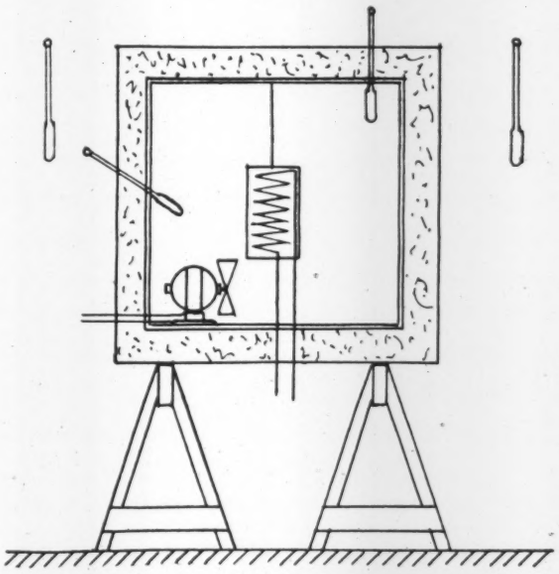

FIG. 4 THE HOT-AIR-BOX METHOD

the temperatures uniform throughout. Absolute uniformity of the temperatures is seldom attained, even with a fan, and the fan further complicates conditions by causing abnormal air currents which may influence the results. The use of lamps as heating elements is unsatisfactory unless they are carefully shielded to prevent direct-radiation effects on the walls as well as on the thermometers used for measuring the temperatures. A resistance coil of sufficient capacity to give the desired amount of heat at relatively low temperatures has been found to be more satisfactory than lamps as a heating element.

Much effort has been expended in devising constructions that would eliminate some of the disadvantages of the simple hot-air-box method. The hot-air-box method has appealed to many investigators because it seems to more nearly approach the conditions of actual service than any other and because it enables both the inside and outside surface factors to be determined at the same time that the conductivity or the transmittance is measured. There have been numerous modifications of the simple hot-air box, such, for instance, as the postal box of the U. S. Post Office Department and the cubical-heater test box used some years ago at The Pennsylvania State College but long since superseded by the guarded flat-plate heater because of the greater accuracy and reliability of the latter.[4]

THE GUARDED HOT-AIR BOX

The box method of testing has probably reached its highest development in the guarded hot-air box, the essential features of which are shown in Fig. 5. In this method an inner insulated chamber, with one side open, is mounted against the material to be tested. In order to prevent the escape of heat except through the material under test a second insulated chamber surrounds the inner one. Each chamber is provided with means for measuring the temperature at various places. An effort is made to obtain uniform and equal temperatures within the two chambers. For this

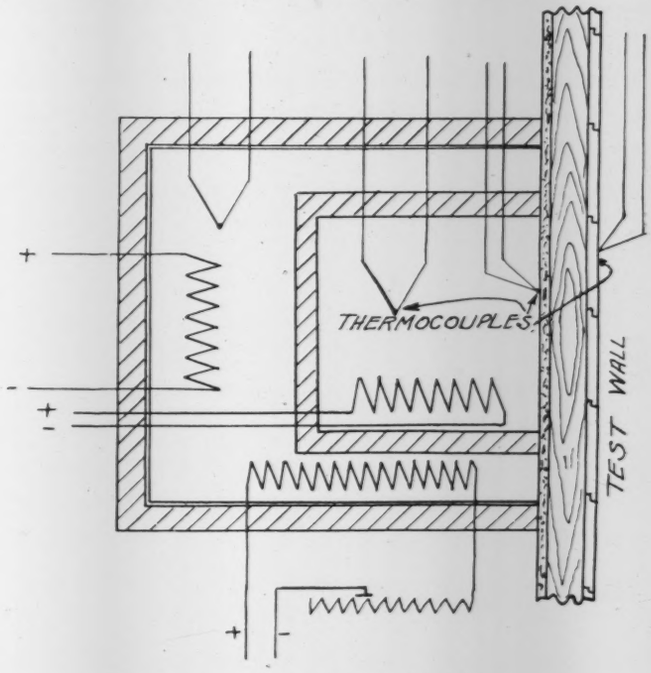

FIG. 5 THE GUARDED-HOT-AIR-BOX METHOD

purpose some experimenters have used a fan to insure a positive air circulation, while others have endeavored to prevent circulation and have tried to secure uniformity of temperature by a careful location of the heating elements. The available published data show that neither method accomplishes the desired result; it seems almost impossible to secure a uniform temperature throughout either the inner or the guard chamber, or to have the same mean temperature in both chambers. As Professor Barker remarks, "The difficulties of maintaining this identity have to be experienced to be properly appreciated."[5] To allow for the temperature differences a correction determined from a calibration test is usually made. If a temperature equilibrium can be obtained, all of the heat supplied to the inner chamber passes through the central portion of the test blank in a normal direction, all edge losses being supplied by the guard heater. Some uncertainty exists as to the exact limits of the test area because the joint between the inner box and the test wall has an appreciable width. The elimination of all corners and edges from the test area assures practically normal heat flow, the only disturbance being due to the contact area between the box and the wall, which probably is not serious.

CONDENSATION METHOD

The steam-condensation method is essentially a hot-box method in which steam is used as the heating medium and in which the heat flow is calculated from the weight of steam condensed and the heat content corresponding to the observed conditions of pressure and quality. This method has been extensively used for determining the relative efficiencies of various types of steam-pipe coverings.

[3] R. Biquard, Efficiency of Insulating Materials for Refrigerated Rooms, Proc. Second Refrig. Congress, Vienna, 1910.

[4] For a full discussion of the construction and use of both the cubical and postal test boxes, see Bulletin No. 33 of the Engineering Experiment Station of The Pennsylvania State College, by E. F. Grundhofer.

[5] Special Report No. 4, British Building Research Board.

In its simplest form it consists merely of a convenient length of pipe of the proper size completely covered with the insulating material to be tested. The pipe is supplied with steam of known quality and the condensate is drawn off and weighed. The temperature of the steam is taken as the temperature of one side; the outer temperature is taken either as that of the outer surface or of the air, depending on whether the conductivity or the transmittance is desired.

The results obtained with this simple arrangement are erratic and liable to serious errors. The principal sources of error are the indeterminate effects of the ends of the pipe, which do not transmit heat at the same rate as the walls; the difficulty in maintaining a steam supply that is dry, with the possibility that some moisture may be carried over at times; and the uncertainty whether the condensate will drain out uniformly without pocketing from time to time.

To overcome some of these difficulties a guard method has been used. This eliminates the indeterminate end losses and may also provide a protecting jacket for the entering steam and for the condensate from the measuring chamber.

DISADVANTAGES OF BOX METHODS

We have already noted some of the ways in which the various "box methods" for measuring heat transmission may be unsatisfactory; the disadvantages cited have to some extent been peculiar to the particular method under discussion. However, there are also certain defects which are more or less inherent in practically all box methods.

Effective Area of Box. Several methods of computing the effective area of the box to allow for the so-called corner and edge effects may be used. The arithmetical mean of the areas of the inner and outer surfaces may be taken, or we may compute the area from the mean linear dimensions, that is, the area of the surface taken at the middle of the thickness of insulation. The former method, which gives a slightly larger area than the latter, seems to have been used more frequently. A third method has also been proposed, namely, to find the volume of the outer and inner cubes and then to find the effective area by dividing the difference between the volumes by the thickness. This gives a result intermediate between the first two. Again, we may take the geometrical mean of the inner and outer surfaces of the box. This gives a result lower than any of the above methods.

At the corners the heat flow is not normal to the surfaces, but flows out along diverging lines, so that none of the above methods are theoretically correct. The proper surface area may be computed by using the shape-factor formula developed by Langmuir, Adams, and Miekle,[6] which for the case of a hollow cube has the following form:

$$S = \frac{A}{t} + 0.54\,\Sigma l + 0.15\,nt$$

where A = inside surface area in sq. in.
t = thickness in inches
Σl = sum of the lengths of the inside edges in inches
n = number of corners of the cube = 8.

It is interesting to compare the result obtained with Langmuir's equation with those of the methods previously discussed in which the shape factor is taken as A/t, where A has values determined as indicated. The results, expressed in square-foot units, are as follows for a 30-in. cube covered on all sides with a uniform layer of insulation 3 in. thick, making the outside dimensions 3 ft. × 3 ft. × 3 ft.:

$$\frac{\text{Arithmetical Mean of Outer and Inner Surfaces}}{3} = \frac{(3 \times 3 \times 6) + (2.5 \times 2.5 \times 6)}{2 \times 3} = 15.25$$

$$\frac{\text{Area Computed from Mean Dimensions}}{3} = \frac{2.75 \times 2.75 \times 6}{3} = 15.125$$

$$\frac{\text{Difference in Volume of Outer and Inner Cube}}{\text{Thickness in Feet} \times 3} = \frac{27 - 15.625}{3/12 \times 3} = 15.167$$

$$\frac{\text{Geometrical Mean of Outer and Inner Surfaces}}{3} = \sqrt{\frac{54 \times 37.5}{3}} = 15.00$$

Using Langmuir's formula for shape factor, we have

$$S = \left[\frac{6 \times 30 \times 30}{3} + (0.54 \times 12 \times 30) + (0.15 \times 8 \times 3)\right] \div 144 = \frac{1800 + 194.4 + 3.6}{144} = 13.875$$

Langmuir's equation gives an effective area 9 per cent less than the usual method of using the arithmetical mean of the inner and outer surfaces. If the thickness of the insulation is increased relatively to the size of the box the difference becomes more pronounced. So far there has been no agreement fixing the method to be used, and hence we should not expect to have results that agree. Langmuir's formula appears to be the most logical method for computing the effective area; its use would give higher values for heat transmission than have been reported by experimenters using the earlier box methods. This difficulty does not occur in the guarded-box method.

Non-Uniformity of Temperatures. In none of the box methods so far devised are the temperatures exactly the same in all parts of the chamber, neither is there any assurance that the temperature at any given point will stay constant during a test. Variations of one or two degrees, or in general from 1 to 2 per cent for the usual temperature ranges, are about the minimum that can be obtained under favorable conditions. This lack of stability of the temperatures makes it difficult to establish a true thermal equilibrium or to apply a satisfactory correction to allow for the variations.

Temperature Measurements. When measuring the transmittance, that is, the heat transmission from air to air, the problem of obtaining the two air temperatures presents no special difficulties; they may be read satisfactorily either with thermometers or with thermocouples, which should be shielded from direct radiation. At each surface there is a temperature gradient the shape of which depends on various factors, such as air movement, humidity, nature of surface, etc., so that the distance from the surface at which the air temperatures are taken may change the results materially.

When surface factors and conductivity values are desired in addition to transmittance, the method of taking the surface temperatures is exceedingly important. Thermometers have been used for this purpose in various ways. Sometimes they have been placed against the surface and covered with a protecting shield, sometimes they have been partly buried in a groove in the surface, and sometimes completely buried so that they were flush with the surface. Their bulk militates against satisfactory results. Probably the most satisfactory method is to use copper-constantan thermocouples of about No. 35 B. & S. gage. The couple bead is in this case small enough to be accurately in the plane of the surface where it can be shielded from direct radiation by a thin covering. To prevent heat conduction along the leads they should be run in the constant-temperature surface for several inches before going to the potentiometer.

Direct Radiation and Convection. The loss of heat from a surface depends on various factors such as its temperature and the nature of the surface, whether it is smooth or rough, bright or dull, etc. Not only is heat given off but it is also absorbed from nearby objects, which may result in a change in the loss of heat from the surface. The air itself absorbs heat by convection and by conduction. The amount removed by convection depends on the air movement, and this in turn is a function of the temperature difference between the surface and the air, and also of the dimensions and shape of the room and of the position of the test surface. For example, it is obvious that the heat loss from a vertical surface is

[6] Trans. Am. Electrochem. Soc., vol. 24 (1913).

different from that of a horizontal one with the heat source beneath, while a horizontal surface with the heat source above will give still a different result. The heat given off by radiation is relatively small in comparison with that carried away by convection.

Metz and Behm[7] have pointed out that the effect of these factors is such that the amount of heat given off by a surface at a given temperature will not be a constant if the tests be made in different rooms, even though they have the same air temperature. Hence it should be apparent that determinations made by different box methods, and in various places, can only roughly agree, even when all are made with care and accuracy. When the results are affected by so many variables it would seem to be impracticable to standardize any of the foregoing methods for measuring heat transmittance.

SUMMARY AND CONCLUSIONS

All of the box methods discussed are essentially laboratory methods and are intended to be applied under laboratory conditions which are more or less under the control of the experimenter. We have seen that all are subject to variable influences, such as temperature fluctuations, air currents, radiation, etc. It is difficult to evaluate these disturbances, and it is doubtful whether their effect can be adequately corrected for. These effects restrict the use of the box method and would seem to preclude its use for the determination of absolute values of heat transmission, either transmittance or conductivity. In the hands of a skilled experimenter and under properly defined conditions the box methods may give valuable useful relative data which may be as accurate as data determined by a less skilled investigator by methods which are fundamentally less subject to error.

Transmittance has a very useful place in the work of the engineer, but its use for expressing the thermal properties of a material has nothing to recommend it. It may be influenced to entirely too great an extent by the value of the surface-resistance factor. Thus Biquard shows that for a solid cork wall 0.25 m. (9.84 in.) thick the sum of the two surface resistances is only 4.5 per cent of the total resistance from air to air, for a stone wall 0.2 m. (7.87 in.) thick the surface factors account for 68 per cent of the total resistance, and for glass 0.03 m. (0.13 in.) thick they account for 99 per cent of the total resistance. Obviously a factor that has such a variable effect should not be included, and if we wish to use the methods under consideration the data should always include the conductivity for a homogeneous material and the conduction for non-homogeneous specimens. The surface factors are important and must be known, but they should be reported separately.

Appendix No. 1

HEAT-TRANSMISSION TESTS UNDER SERVICE CONDITIONS

THE methods previously discussed have all been essentially laboratory methods for determining the thermal properties of building and insulating materials under carefully fixed conditions, and usually with a moisture-free test specimen. Such conditions are seldom or never found in practice.

To secure information regarding heat transmission under service conditions two methods have been used. The first is an extension of the hot-air-box method using either a test house or a guarded hot box on a building wall; the other method makes use of "heat meters" previously calibrated—usually by the guarded-hot-plate method, which is fully treated in another report of this committee.

The Test House. In this case small huts, or single-room houses, are built identical in every respect except in the construction of the walls. The houses are placed in an open location where the exposure will be the same for all. Each is provided with an electrical heating element to maintain the desired temperature. Because of the variable outside conditions thermal equilibrium is never reached, and it is necessary to continue the test for a sufficient length of time to eliminate, so far as possible, the effect of the fluctuations. Results are usually computed for the entire heating season, and hence represent a sort of average value of the transmittance and surface factors for service conditions.

The losses through the walls will differ materially from those through the floor and roof, even though a similar construction is used throughout, however, the loss through each cannot be definitely determined. An estimate of the separate losses may, however, be made by using a guarded box heater on the individual walls.

This method is intended primarily to give comparative values for various wall types under working conditions as regards wind, rain, moisture, sunshine, etc. Unfortunately, the initial cost of the test houses is high, and in most parts of the country the period during which they can be successfully used is limited by the weather conditions.

[7] Friedr. Rud. Metz and A. Behm, 2nd Int. Cong. of Refrig., Vienna, 1910.

This method of testing has been most extensively used by Professor Bogge at the Norway Institute of Technology, Trondhjem, Norway. Similar tests have been made by Professor Grieg at the University of Saskatchewan. Professor Barker at the University of London has made a few tests of the heat flow through the walls of an old building with a guarded hot box.

The Heat-Meter Method. The most recent development for measuring heat transmission under working conditions is the "heat meter" or standard thermal resistance. By its use the heat flow through any type of flat wall of an actual building may be determined with a minimum disturbance of service conditions. The heat meter consists of a thin flat plate of any convenient size and material laced with a large number of copper-constantan thermocouples to give the temperature difference (usually in millivolts) of its two faces. Another group of thermocouples is used to give the surface temperature (also in millivolts). From the relation between these values and the use of a calibration curve the heat flow is found.

The meter plate is mounted on the wall, floor, or ceiling, the heat transmission of which is to be measured, and readings are taken, say, every half-hour over an extended period of time (usually several weeks) of the surface and the differential millivoltages by means of a potentiometer. From these data, and a previous calibration of the meter plates, which is usually made by the guarded-hot-plate method, the rate of heat flow is readily determined. A slight correction is usually necessary to compensate for the extra resistance which the meter adds to the wall. To determine the complete thermal properties of the wall it is also necessary to measure the inside and outside air and the wall surface temperatures. These are readily obtained with thermocouples.

This method is relatively cheap, requires no special facilities in the way of test rooms, and can be readily applied to a flat wall of any type. The possibility of determining the effect of length of service, moisture, deterioration of materials, etc., on the heat transmission renders this method exceedingly attractive. The meter should be of sufficient size to cover a representative section of the wall under test. Nicholls used plates 2 ft. by 2 ft. while those used at The Pennsylvania State College are 3 ft. by 3 ft.

The only important published data on this method and on the results obtained are to be found in two papers by P. Nicholls.[8] Considerable work along similar lines has been done at the Bureau of Standards and at the Engineering Experiment Station of the Pennsylvania State College.

RESULTS OF SERVICE TESTS

The results of service tests made by these two methods are briefly discussed in the bibliography forming Appendix No. 2, and in general confirm the validity of the usually accepted values for heat transmission.

The term "transmittance" seems to have a more logical basis for use in connection with heat flow through the walls of actual structures than with materials tested under laboratory conditions, and if it is to have a recognized place in heat-transmission data it might be well to restrict it to that use. In this event the heat meter, or some modification thereof, might well be chosen as the recommended method for its determination. No general agreement of results obtained need be expected, however, because of the influence of many of the variable factors which have already been discussed in connection with the box methods of testing.

Appendix No. 2

BIBLIOGRAPHY

IN THIS section it is proposed to discuss briefly some of the more important contributions on the subject of heat transmission and to limit it principally to those dealing with methods that have been used for, or are adapted to, the determination of transmittance.

1 Report of Professor C. L. Norton to Armstrong Cork Company on Insulation Tests, 1910. Given in full in Armstrong Cork Company's book Non Pareil Corkboard.

Professor Norton used five methods: namely, ice box, oil box, cold-air box, hot-air box, and a small flat plate electrically heated but without a guard annulus to prevent edge leakage. Each method is described in considerable detail. In general Norton seems to have determined conductivity, but in describing the hot-air box he twice refers to the temperature difference between the air inside the box and in the room outside. It is also significant that his illustrations show no means for getting surface temperatures, neither does he mention how they were obtained except in the case of the flat plate where thermocouples were used.

No original test data are given from which the constancy of conditions can be determined, but the average values obtained from a long series of tests on cork and lith were as follows. The values are in B.t.u. for 24 hr. per inch per deg. fahr., and are assumed to be conductivities:

Method	Cork	Lith
Ice box	6.1	7.9
Oil box	6.4	8.4
Hot-air box	6.9	9.8
Cold-air box	6.0	9.7
Flat plate	6.7	9.0
Mean	6.4	8.9

For cork the maximum variation occurs between the values obtained by the hot-air-box and the cold-air-box methods and amounts to 15 per cent; for lith the maximum variation, which amounts to 24 per cent, is between the values from the ice box and the hot-air box. Norton discusses the probable relative accuracy of the various methods used and concludes that the

[8] Measuring Heat Transmission in Building Structures and a Heat-Transmission Meter, *A.S.H.&V.E. Journal*, Jan., 1924, and Practical Applications of the Heat Flow Meter, *A.S.H.&V.E. Journal*, June, 1924.

hot-air box and the cold-air box are the most reliable. He states that with the hot plate results can be readily duplicated within one per cent, yet, curiously, he remarks that the method is better adapted for giving relative results rather than absolute values. The absence of a guard ring, which made it difficult to allow for the edge loss with thick sections, may have led to this conclusion, which is directly contrary to our own.

No information regarding the physical properties of the cork is given; we may assume, however, that it was uniform and that the variations in results are due to test errors. Tests made by the Armstrong Cork Co., using the box method at their Pittsburgh testing laboratory, gave a value of 6.2, while Mr. Walter Kennedy obtained a value of 6.5 in B.t.u. per 24 hr. per sq. ft. per inch thickness per deg. fahr. when using the company's plant, and presumably the same material. The values reported are too low to be conductivities if the usual grade of corkboard (weight from 9 to 10 lb. per cu. ft.) was used, but would correspond approximately to the transmittance.

2 Starr Engineering Company's Tests for Union Fiber Co., 1911. Reported in the Union Fiber Company's book Insulation for Cold Temperatures.

These tests were made with an improved form of ice box, 3 ft. by 3 ft. by 3 ft. outside fitted with baffles to promote circulation. Each test was run from six days to two weeks, from 48 to 60 hours being required to reach equilibrium conditions. The area of the box was computed from the mean linear dimensions and the temperatures were taken with mercury thermometers placed $\frac{1}{2}$ in. from the surfaces.

The average daily temperatures are tabulated for several successive days and show considerable variation. The variation between inside and outside temperatures for successive days is sometimes large without a corresponding change in the heat flow. For instance, one test shows a temperature difference of 22.28 deg. fahr. with a unit heat flow of 3.06 B.t.u., while the following day the temperature difference increased to 28.29 deg. fahr. with a heat flow of only 3.07 B.t.u. In other words, the temperature difference varied 27 per cent without any recorded variation in the heat flow. The maximum variation for the transmittance computed from the test data is 37 per cent.

3 A Study of the Heat Transmission of Building Materials. Bulletin No. 102 University of Illinois, 1917, by Willard and Lichty.

A brief discussion of various methods of testing. The authors adopted the hot-air-box method, using a vertical rectangular box having the general proportions of a column. In the still-air tests the temperatures were measured with thermocouples as well as with mercury thermometers. In most instances there is a marked difference between the values; usually the temperature obtained with the thermocouples is the higher, though there are exceptions to this general rule. The authors state that the thermocouple values are considered the more reliable. An inspection of the results obtained for the conductivity of 2-in. corkboard confirms this conclusion, because the values agree closely with those obtained elsewhere for material of similar density. Values for transmittance, conductivity and for both surface factors are given for three heat flows for each material. The results show wide and erratic variations and follow no definite law, indicating that the difficulties of obtaining a true thermal equilibrium were not entirely overcome.

4 Heat Transmission—Corkboard and Air Spaces. Bulletin No. 30, Penna. State College, 1920. Wood and Grundhofer.

A report, with complete original data, of an extensive series of tests with two types of hot-air boxes, namely, the postal box as developed by the Post Office Department, and the cubical heater box designed and built at the College. The test boxes were placed in a special insulated test room the temperature of which could be kept constant by cold-brine circulation. The heat was applied electrically. The temperatures were measured with specially designed resistance thermometers. However, in spite of almost ideal conditions and careful manipulation it was difficult to secure concordant results. The postal box was found particularly unsatisfactory. For a complete analysis of the results obtained by these two methods and a comparison with those of a large cubical box ($6 \times 6 \times 6$ ft.) and a guarded flat-plate heater, see Bulletin No. 33, Pennsylvania State College, 1925, entitled An Investigation of Certain Methods for Testing Heat Insulators, by E. F. Grundhofer. The unsatisfactory features of the various box methods are pointed out and the reasons for abandoning them in favor of the guarded hot plate are given. The box methods have not been used at Pennsylvania State College since 1920.[9] For certain purposes the flat-plate method is used in conjunction with the constant-temperature cold room; this permits determining the surface coefficient on one side as well as the surface temperature gradient.

5 Transmission of Heat Through Building Materials. Bulletin No. 3, Engineering Experiment Station, University of Minn., 1923, by Frank B. Rowley.

A guarded hot-air box with one open side was used in determining the relative transmittance of various kinds of insulating materials used in building construction as well as of light compound wall sections of a type frequently used in residences.

The heating elements were electric lights, the direct radiation from which may have influenced the results in some cases, although the author states that shielding the lights had no noticeable effect on the results except in the case of glass. Natural convection was depended upon to give a uniform temperature in the inner box, which was of course not attained. On the other hand, a fan was used to circulate the air in the outer, or guard, box; with the exception of one thermometer, which does not seem to have been in the air stream, the temperatures in the guard box show good agreement, although there is considerable fluctuation between successive readings. The use of the fan undoubtedly affected the rate of heat flow through the guard area of the test specimen, making it different from the flow through the central area and resulting in a distortion of the flow lines. The results are valuable and interesting as a comparative study, and are an example of the field in which the box method may be used to advantage for determining relative values for the transmittance of various kinds of walls. The results are not absolute values and may or may not be useful for computing the heat loss for combinations of similar materials in types of construction other than those tested.

[9] See also Houghten and Wood, *A.S.H.&V.E. Journal*, July, 1921, vol. 27, no. 5.

6 The Transmission of Heat Through Heavy Building Materials. Bulletin No. 2 of the Institution of Heating and Ventilating Engineers, London, by Arthur H. Barker. See also Special Report No. 4 of the Building Research Board (British).

A discussion of the difficulties encountered and the sources of error in heat-transmission tests made by the guarded-hot-air-box method. The data are quite complete and show the difficulty of maintaining constant temperature conditions. A correction is applied to compensate for the lack of balance; this ranges from 0 per cent to a maximum in one case of 26 per cent. Professor Barker has computed the inside and outside surface factors as well as the transmittance and conductivity.

In addition to the series of laboratory tests, tests were made on an old 9-in. brick wall covered on the inner surface with $\frac{1}{4}$ in. of plaster. By keeping the room temperature the same as that inside the test chamber attached to the wall under test, the method was equivalent to a guarded hot-air box. The transmittance values show wide variations from time to time; in general high values accompany wind and rain, while sunshine and absence of wind and rain favor a low coefficient of transmittance. The mean value for the transmittance is 0.401, which Professor Barker remarks is some 22 per cent greater than the figures given in current English tables for such a wall; comparing it with the values commonly used in the United States, it is approximately 14 per cent greater.

7 Heat Loss Through Wall Constructions, by Alf Kolflaath, *A.S.H.&V.E. Journal*, September and October, 1924.

A presentation of the results obtained with twenty-seven small test houses constructed at the Norway Institute of Technology, Trondhjem, Norway. All of the houses were tested for relative heat losses under similar conditions; in addition six types of wall construction were tested by a guarded-box method to determine the actual heat losses and the surface coefficients. From the "box" tests the experimenters reached the important conclusion that the sum of the inner and outer surface resistances is equal to unity for usual service conditions. This value is about 5 per cent higher than that obtained by taking the inside surface coefficient as 1.40 and the outer surface coefficient as 4.20, which are approximately the values often used. Attention is drawn to the influence of daylight on the outside-surface factor. During the daytime the temperature difference between the outer wall surface and the outer air is greater than at night, even on a north wall, which does not receive the direct rays of the sun. To some extent this effect is manifested even on cloudy days. A similar effect has been observed at the Pennsylvania State College on an 18-in. brick wall with an eastern exposure. Furthermore, when the sun shone on the wall the temperature difference between the outer wall surface and the outside air rapidly increased from a value of 5 to 8 deg. fahr. to as much as 40 deg. and, due to the warming up of the wall by the sun's rays, did not fall off to its normal value until about six hours after the wall was again in shadow.

In general the houses of wooden construction showed lower heat losses than those of brick. With the brick constructions the advantage of an inside coat of plaster, presumably with an air space, is marked as it reduces the transmittance about 20 per cent.

The conductivity coefficients for the brick walls varied between 4.8 and 7.3, depending on whether the brick were medium or hard burned and whether they were placed in the inner or the outer part of the wall. Tests showed that in one house the average moisture content of the inner bricks was 0.3 per cent by weight and 2.0 per cent for the bricks in the outer part of the wall. However, there was a wide variation in the amount of moisture from brick to brick, and even in different parts of the same brick, so that it was difficult to fix a true average. Bricks tested by a plate apparatus at the same institution gave for a dry medium-burned brick (112 lb. per cu. ft.) a conductivity of 4.1 and for the same brick with 10 per cent moisture a conductivity of 5.4. The high conductivities obtained in service tests are attributed to the effect of the mortar joints particularly where both medium- and hard-burned brick which are of different sizes were used in the same wall.

8 Measuring Heat Transmission in Building Structures and a Heat-Transmission Meter. *A.S.H.&V.E. Journal*, January; 1924 and Practical Applications of the Heat Flow Meter, *A.S.H.&V.E. Journal*, June, 1924, by P. Nicholls.

Two valuable papers dealing with the design, construction, calibration, and practical application of heat meters. The calibration curves for fifteen meter plates of various kinds of materials are given. The plates were all 2 ft. square with a central measuring area 15 in. by 15 in. and varied in thickness from $\frac{1}{16}$ in. to $\frac{1}{2}$ in. In general the consistency of the results shows that the work was done with great care; the inclusion of some of the original calibration data would, however, have added materially to the value of the paper.

The second paper, dealing with the application of the meters to the walls of buildings, is of particular interest in emphasizing the adaptability of the heat meter for measuring the heat transmission of structures under service conditions. This represents the most convenient method that has up to the present been developed for this purpose, and by using several meters a number of tests can be carried out simultaneously with a minimum of equip-

ment and personnel. The most obvious disadvantages are the necessity of continuing the tests for a considerable length of time to allow for the constantly changing conditions, particularly outside, and the fact that readings must be taken day and night throughout the test.

Data for several kinds of walls are given; though the values for brick walls do not differ much from those generally used, they are all somewhat higher than laboratory determinations made on dry walls. The value 11.35 obtained for the conductivity of a concrete foundation wall 26.2 in. thick is about 40 per cent higher than the value often used for such walls. The sum of the inside and outside surface resistances for the various walls is greater than was found in the Norwegian tests. The value of the outside-surface factor is influenced greatly by the weather conditions, particularly wind and sunshine. With a high wind the temperature gradient between the wall surface and the air will be quite small; on the contrary, if a wall is exposed to sunshine it is possible that the temperature difference may become abnormally high.

9 New Apparatus for Determining the Coefficients of Conduction of Heat by F. Rud. Metz and A. Behm. Proceedings of the Second International Congress of Refrigeration.

The authors discuss the requirements of a satisfactory apparatus for heat-insulation tests and review the methods commonly used. A guarded tubular and a flat-plate method, using steam as a heating medium, developed by the authors are described. The paper is chiefly of interest because of the excellent discussion of the various factors which affect the results obtained with box methods and the conclusion that the results obtained by such methods are of comparative value only. The following paragraphs are quoted directly from their paper.

"A very large number of factors have influence on the results of these trials. We have already mentioned that, in determining the effective value, the loss of heat of the insulated must be compared with the loss of heat of the non-insulated tube. Upon what, however, does the latter depend? Chiefly, certainly, upon the surface temperature, but also upon the condition of the surface—whether it is smooth or rough, whether it is of cast iron, copper, wrought iron, etc.—for these factors are calculated to influence the amount of surface radiation. As a tube, however, not only gives off heat but also absorbs heat, objects near to the experimental object if they give off great heat (stoves, steam heating) can influence the result by decreasing the loss of heat of the bare tube. But the surrounding air also absorbs heat, and that in two ways—by conduction and by convection. The amount absorbed by convection depends, naturally, upon the rate of motion and temperature of the moving air. Such motion, however, arises even from the heating of the air on the tube itself, and the amount of motion is here a function of the space and dimension as also of the position of the steam tube in the room and of the surface temperature of the tube. The quantity of heat absorbed from the tube by the surrounding air is inconsiderable in comparison with that absorbed by the ever-present air current. I will not tire by recounting further factors, those already mentioned will fully suffice to show that the amounts of heat given off by a tube of definite surface temperature and condition will not be constant even if the examination be made in different rooms having the same air temperature. From this, however, it is evident that it is absolutely necessary, when stating the results of such experiments, to give data which shall make it possible to reach conclusions, based so far as possible upon the influence that all these factors had on the result of the experiments. It is also necessary to state the dimensions of the room in which the experiment was conducted, the position of the experimental object in the room and any sources of extraneous heat present. The air temperature in various parts of the room must be known, as also the air motion near the tube, and all factors that are calculated in any way to influence the results of the experiments. It is plain that such determinations made with various apparatus in various places can only roughly agree. Exactly the same factors as those calculated to influence the heat radiation from the bare tube influence the heat radiation from the insulated tube. From the nature of many factors it is evident that their influence is greater in the first case than in the second. For instance, the air motion over the bare tube is, under similar conditions to those here, simply a function of the surface temperature. But the surface temperature of the bare tube is very different to that of the insulated tube. Therefore, the amount of heat radiated from the insulated tube, in spite of the same temperature difference between air and steam, must be variable, especially if determined at different places with different apparatus. In all the above cases we have seen that the determination of the effective value of an insulation according to the methods described only possesses strict validity for the experimental room and apparatus, and that the application of such determination to other conditions and rooms cannot be made without further investigation if absolute exactitude of value is important.

"Frequent repetition of such trials under different conditions enables it to be easily seen how large are the variations to which the efficiency is subject owing to the above reasons. Our tubular apparatus was made transportable in order that the efficiency of the same insulation material might be determined at various places, and in buildings and open places without difficulty. If I have dilated upon this point more fully than was apparently necessary, I did so for a special reason. So long, namely, as we make use of efficiencies so obtained for technical calculation we shall make no great errors, provided that the above-mentioned factors do not possess quite other dimensions in practice than in the experiments. Should this be the case it is still possible by a sensible correction of the efficiency to allow for the changed factors. It is quite a different matter, however, when such data regarding efficiency are used to compare two different competing insulating materials. If the efficiencies are determined with various apparatus at various places and perhaps, too, at various temperatures, then the error made in such comparison may, as already stated, be far greater than the difference in the actual insulating values of the two materials. Indeed this can go so far that the material for which the smaller efficiency is found may possess the better insulating quality. If it is not possible, when determining the efficiency, to allow for the value of individual factors that every uncertainty of result is overcome, much less can the influence of these factors be allowed for in determining the efficiency of an insulation from the coefficients of its heat transmission, and, consequently, efficiencies obtained on computation basis even with exact coefficients of heat transmission must have far greater errors than exist in the particular efficiencies. In recounting these factors I have, for special reasons, only mentioned those which arise from the method or the apparatus. If, however, most of the factors mentioned here are eliminated by artificial obtention of a constant temperature gradient, there yet remain a large number of such factors whose value it is absolutely necessary to know if it is desired to obtain exact results.

"We have also recognized that exact comparisons between the values of different insulating materials can only be made on the basis of the coefficients of their heat transmitting powers. Before we proceed, however, to more closely consider the requisite apparatus and methods, we must not omit to mention that in determining the efficiencies, if a determination of the influence of individual factors is simultaneously undertaken, the foundation can be laid upon which it might, perhaps, be possible in the future, with the aid of correct coefficients of thermal transmission, to calculate the efficiencies of insulations more exactly than heretofore."

10 Modern Methods and Investigation Results for Determination of Heat Transmission, by Oscar Knoblauch, *Zeitschrift für die gesamte Kälte-Industrie*, vol. 29, no. 10, October, 1922.

The author discusses the errors that occur, due to the absorption of radiant energy, when ordinary thermometers are used for measuring air temperatures. He shows how the true temperature may be determined by using two thermometers, one with a plain glass mercury bulb and the other with a bulb covered with gold, silver, or nickel.

The use of a "heat meter," made of glass 2 mm. thick and 10 cm. by 10 cm. in area, is described. The quantity of heat flowing through a wall to which the meter is applied is determined from the difference in temperature of the two sides of the glass plate, as measured with resistance thermometers, and the known conductivity of the glass. The method requires extreme care in measuring the temperatures to insure accuracy.

New Methods of Lubricating Steel-Mill Machinery

Requirements in Lubricating Oils—Characteristics of Lubricants Suitable for Gears and Journals—Gravity- and Pressure-Type Lubricating Systems—Rates at Which Oil Should Be Supplied, Etc.

By CHARLES H. BROMLEY,[1] FORT WAYNE, IND.

THE purpose of this paper is twofold: first, to describe new methods of lubricating the bearings and gears of mills; second, to plead with users of such methods to compile performance data that more may be available. The newer methods of lubrication, as related to application, filtration, circulation, and cooling of oils, form so new a branch of the industrial arts that more and better data are needed. While the data furnished by manufacturers of such lubricating and conditioning systems and by oil companies are good, the best will be available only as the engineer-users contribute to their compilation.

Properly cared for in use, "straight-run" mineral oil does not wear out in the sense that it suffers material change in state and of constituents. The stability of character of the lubricant makes easily possible the maintenance of its lubricating properties over a long period of time. Because it may be used over and over again, if properly reconditioned, it may be continuously circulated in adequate volume to bearings and gears and thus vastly improve lubrication as compared with all other methods. This fact is rapidly promoting the adoption for all classes of heavy machinery of oiltight bearings and gear cases that permit of continuously flowing a stream of clean, cool oil to the working surfaces and overflowing the used oil out again. Hot necks and cold necks are not included in the systems here described except that oil is used in the roller bearings of reinforcing rolls of four-high, one-pass stands.

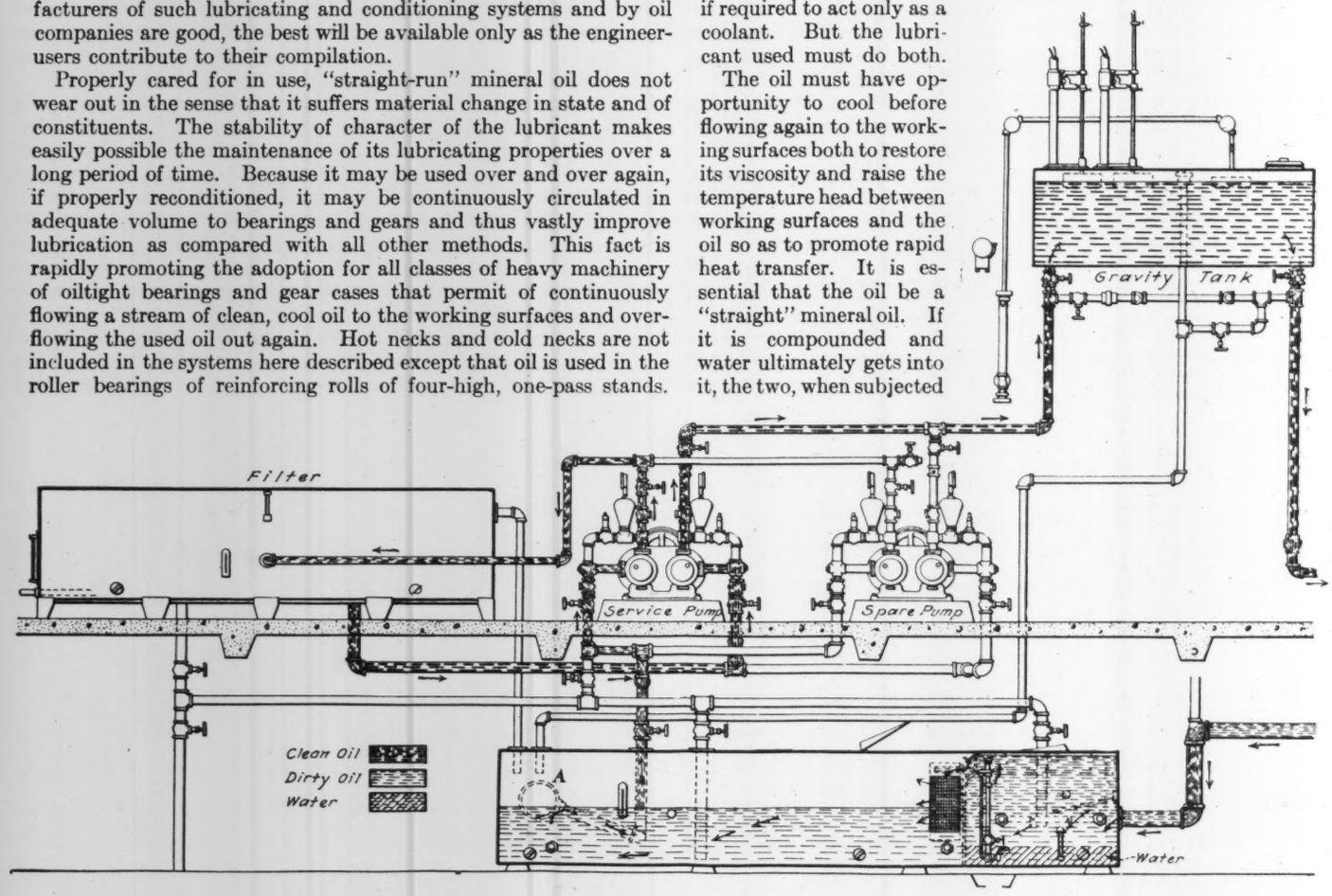

FIG. 1 DIAGRAMMATIC LAYOUT OF CONTINUOUS OILING AND FILTERING SYSTEM, GRAVITY TYPE

Steel-mill machinery particularly benefits from this, as bearings and gear cases so designed and provided with a lubricating system make necessary only one oil for both bearings and gears. Consequently there is immediate freedom from the emulsion troubles so persistent where bearings use oil and the gears some viscous compound. Water is usually present. The compound works its way along the shaft to the bearings, or oil gets mixed with the compound in the gear case. If water is present with oil and compounds, emulsions, sometimes permanent, are formed.

OIL MUST COOL AS WELL AS LUBRICATE

With the ever-increasing trend toward higher journal speeds and loads, and higher tooth pressures and speeds for gears, the lubricant must function largely as a coolant at the same time that it reduces friction. Therefore the characteristics of the lubricant are of vital importance. Obviously, the highly viscous compounds and greases are precluded by their lack of fluid properties. Their specific heats are about the same as that of oil when both are entirely or nearly entirely derived from petroleum. Ordinary light oils must also be excluded because their viscosities are so low at the working temperatures that they lack "body" to lubricate adequately the hard-worked surfaces, though they might serve well enough if required to act only as a coolant. But the lubricant used must do both.

The oil must have opportunity to cool before flowing again to the working surfaces both to restore its viscosity and raise the temperature head between working surfaces and the oil so as to promote rapid heat transfer. It is essential that the oil be a "straight" mineral oil. If it is compounded and water ultimately gets into it, the two, when subjected to high temperature and violent agitation, will result in a serious emulsion. As water is slightly miscible in all oils, "straight-run" or compounded, it is to be inferred from the foregoing that care must always be taken to exclude it, particularly that which splashes from roll necks.

CHARACTERISTICS OF A SUITABLE JOURNAL AND GEAR LUBRICANT

Where journals only, or journals and gears but lightly loaded, are to be lubricated, it is best to use oils of a slightly lower viscosity than where loads are heavy for both gears and bearings or heavier for the gears than for the bearings. The latter is the usual condition. For heavy loads or where large reduction gears are present, a suitable lubricant when continuously cleaned, cooled, and circulated, is a "straight-run" mineral oil having approximately the following characteristics:

Specific gravity	0.905
Viscosity, Saybolt seconds at 100 deg. fahr.	1200 to 2000
Do., Saybolt seconds at 210 deg. fahr.	110 to 120
Flash, minimum, deg. fahr.	490

[1] Assistant to President, S. F. Bowser & Co. Assoc-Mem. A.S.M.E.

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Fire, deg. fahr.	540
Cold test, maximum, deg. fahr.	50

Where there are no gears to be stream-lubricated and the bearings are subjected to the moderate loads prevailing in the steel industry, oil of the following characteristics is suitable:

Viscosity, Saybolt seconds at 100 deg. fahr.	300 to 500
Do., Saybolt seconds at 210 deg. fahr.	60 to 80
Flash, minimum, deg. fahr.	400 to 450
Fire, minimum, deg. fahr.	450
Cold test, maximum, deg. fahr.	45

The author believes it well to use the heavier oil wherever possible on account of its having a relatively high viscosity at the working temperatures. Very seldom will such oil be found to be too "heavy" for the bearings, the working clearance between journal and shell, as commonly allowed in machine design, being adequate to accommodate the oil at its usual viscosity at the usual working temperature. All mineral oils rapidly lower their viscosity on reaching temperatures above 100 deg. fahr. Further, the low surface tension of these oils causes them to have much higher permeative powers than are generally attributed to them by engineers. In other words, the danger of an oil being too "thick" for steel-mill and similar machinery bearings is more imaginary than real, except, of course, that it must flow readily to fulfil its function as a coolant.

Experience has shown that in most applications of continuously filtered oil in streams to bearings and gears, special cooling apparatus is not necessary. With an oil volume sufficient for the projected area of journals and gears, the heat lost from the time the oil leaves the bearing and gear housings until it returns is sufficient to restore the viscosity and reduce the oil to a satisfactory temperature. When extra cooling is necessary, it is easily and inexpensively applicable. The matter of determining extra cooling capacity is one involving only the usual heat-transfer problem as with any other liquid or gas cooled by water. The specific heat of the oil is, of course, taken as 0.5 per deg. fahr.

GRAVITY-TYPE SYSTEM

Fundamental considerations having been presented, the various systems of lubrication may now be described. Fig. 1 shows diagrammatically the general layout of an oil-circulating and filtering system now common in many of the newer installations of various kinds of mills, such as blooming, slab, merchant, bar, or any similar mill. This is a gravity system, wherein the pressure on the oil feed lines is from the hydrostatic head of the oil "leg" from the gravity tank. Fig. 2 illustrates the layout of a pressure system now finding considerable favor because of its simplicity and absence of gravity tanks. (Sometimes the cost of mounting the gravity tank is so considerable as to be an item well worth avoiding, if possible.)

Referring to Fig. 1, oil flows from the gravity tank to the main feed line, from which it is distributed to the various points of lubrication. The oil, after use in bearings and on gears, passes out of the housing through an overflow into the drain main and goes to the precipitation tank, which is always the lowest part of the system. The precipitation tanks should always be placed in a concrete pit, well drained, capable of being heated, and having natural ventilation, yet being closed to the full effects of winter atmosphere. Here the water and heavy entrained solids are removed, also a large part of both the insoluble and soluble sludge. One of the pumps of the twin rotary pump takes oil through the floating suction *A* and discharges it to the filter, where final purification is effected. The other pump takes oil from the filter and discharges it to the gravity tank. This completes the cycle.

PRESSURE-TYPE SYSTEM

The cycle in the pressure-type system, Fig. 2, is the same as in the gravity system, except that the oil from the filter goes to the pressure tank. Pressure switches cut in and cut out the motor-driven pumps, maintaining a predetermined pressure in the supply or pressure tank sufficient to force adequate oil to all points of lubrication. Usually the pressure switches operate within a range of 20 to 40 lb. These systems are provided with relief valves for possible over-pressure and with a continuously ringing gong alarm for too low a pressure.

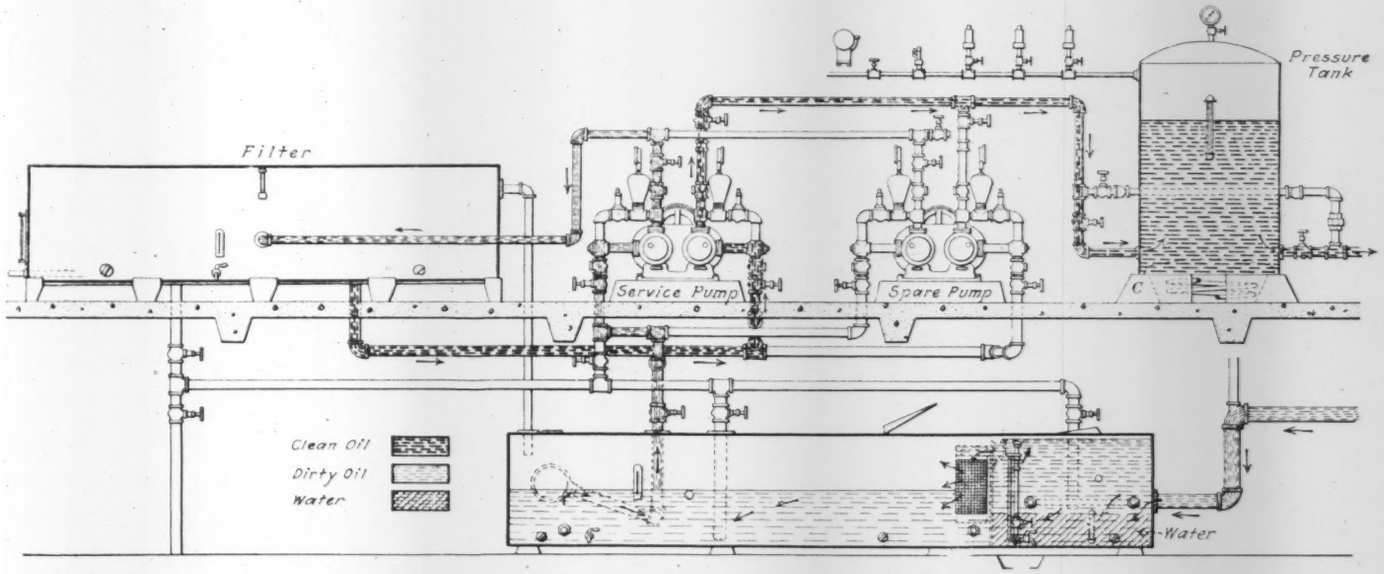

FIG. 2 DIAGRAMMATIC LAYOUT OF CONTINUOUS OILING SYSTEM, PRESSURE TYPE

HEATING FOR OILING SYSTEMS

Heat for the entire oiling system is extremely beneficial in winter. The mill buildings are of the open type, in practically all parts of which the atmospheric temperature is that of outdoors. The heavy oils soon thicken when their temperature gets below 50 deg. fahr., and obviously in freezing weather and colder, flow through the pipe lines would be very sluggish. The gravity, pressure, and precipitation tanks and the filter should therefore always be provided with heating coils for use until the oil becomes liquid enough to flow readily. When the filters and pressure and precipitation tanks are enclosed in simple housings, the heat of the circulating oil keeps the little rooms warm all the time. Further, there is then absence of the condensation of water vapor from the oil on the inside surfaces of the filters and tanks, which keeps down corrosion of these surfaces. As the mains, both feed and drain, are usually very long, 200 ft. or more, excellent results are obtained if a $1^1/_2$-in. steam line is run parallel with the oil line, kept practically next to it, and the two enclosed in light sheet metal kept half an inch away from the pipe by spacers and covered over with an insulating material. Where this is done the lowest of sub-zero weather has no bad effect upon the oiling system. It is best that heating coils for filters and tanks be kept outside them and so placed that they may

efficiently give up their heat to the oil; this avoids leakage of condensate into the oil should the coils leak. In Fig. 2, for example, the coil *C* is under the convex head of the pressure tank and set in a recess in the concrete foundation. These systems are of course equipped with thermometers, temperature regulators, sampling cocks, gage glasses, bypasses, and other such appurtenances as are in keeping with good engineering practice. Obviously, it is important to see that drain piping has sufficient pitch. No fixed pitch is ordinarily possible for all installations. Therefore it is best for the system and its piping to be laid out immediately after the type of mill has been selected and before the concrete pits are made.

Slow Wear of Enclosed Gears When Continuously Flooded with Cool, Highly Viscous Oil

It is interesting to note that enclosed gears such as reduction gears, ordinarily heavily loaded and operating at high speeds, show extremely slow wear when lubricated by a continuous stream of clean, cool, highly viscous oil. The application of this method of lubricating them is too recent (within the last three years) to make available any data on how much it lengthens the life of the gears. But experience shows it to be very considerable—and this should be expected. The oil is injected in large volume upon the teeth at the place and time they mesh. The tooth speed is so rapid that before the oil can drop away or be squeezed out, the teeth pull out of mesh. The fact that the original tool marks remain upon the faces of the teeth after months of operation with gears so lubricated, leads to the conclusion that there is little or no metallic contact, but a liquid one. The condition may be said to be hydraulic. Where the gears simply dip in an oil bath not continuously drained away and resupplied with clean, cool oil, the oil temperature soon becomes so high that the viscosity is impaired too much to maintain this hydraulic condition. The same applies to ring- and collar-oiled bearings, where there is not a continuous drain and supply.

Oil losses in such systems are very low as the systems are closed ones. It is important that the oil volume be adequate when the system is put into operation so that the lowest level in the precipitation tank at any time is at least twelve inches, measured from the bottom of the tank. If the oil volume is inadequate, the number of cycles per unit of time for each gallon is so frequent that proper cooling may not occur. If the level gets too low in the settling chamber of the precipitation tank, the agitation of the dirt on the tank bottom caused by incoming oil may diffuse the dirt through the body of the oil and over-load, possibly plug, the filter units. All openings through which water may get into the lubricating system should be plugged; splash from roll necks is the principal source of water.

Rates at Which to Supply Oil to Bearings and Gears

Where roller bearings are used the foregoing methods of application are well suited. The volume of oil run on to the bearings should be the same or a little greater than for plain bearings.

The volume of oil to circulate to bearings and gears varies according to the particular conditions present on each job. For bearings this volume varies from 30 to 60 sq. ft. of projected area per gal. per hour. For reduction gears $^1/_4$ to $^1/_3$ gal. per min. per lineal inch of face of the gear should be taken as the minimum.

Gears usually require so much oil circulated per hour that the filtration systems are frequently of the partial or bypass type.

Power-Station Accounting for Industrial Plants

Particulars of a System of Procedure That Has Been Employed Satisfactorily with but Minor Modifications for Over Three Years in Seven Factory Plants

By WILLIAM ROGERS HEROD,[1] SCHENECTADY, N. Y.

IN THE manufacturing establishments of modern industry the supply of such services as power, heat, steam for industrial purposes, compressed air, and water is of fundamental importance, and our entire system of manufacturing production is based upon these services being available. Their cost as a general rule, however, is only a small proportion of the total cost of manufacturing operations, such proportion being in fact for many manufacturing establishments only some 3 to 4 per cent of the total cost of product. A generating station for the supply of these services is accordingly frequently regarded by the manufacturer who must make the investment for it, as an evil, necessary only because these services are not procurable elsewhere. This viewpoint has in many cases led to a tendency toward eliminating or reducing to a minimum such metering and measuring devices as should properly be installed, as well as toward an abridgment of the accounting system to a point short of that necessary to properly reflect the true operating conditions in the plant. This tendency has frequently been justified, in the case of smaller manufacturing establishments, on the theory that the cost of supplying these services is a small proportion of the total cost of operations, and that a refinement in accounting practice for them would not be warranted.

But as the business of a company expands, the value of these services becomes greater, and with a large company with more than one factory, the value of these services in the manufacturing departments may total several millions of dollars a year, with the result that their supply, even though not a large percentage of the total in cost, is still a sufficiently large problem to warrant a more or less complete set of accounts and records, as a saving or loss of a few per cent in the operation of these stations or the supply of these services may mean a considerable amount during the year. Accordingly for such a concern it is essential to have an accounting system which will reflect as accurately and from as many angles as possible the true conditions of plant operation, such of course to be consistent with a reasonable amount of clerical and other expense. Such a system should hence be illustrative of:

1 The economy and cost of operation at any individual plant, with a view toward indicating where improvement may be possible.

2 The proper distribution of expenses among the various services on as representative a basis as possible—for example, to steam, power, compressed air, or other services—so that they may be equitably billed to the respective departments and ultimately charged into cost of product in a proper fashion.

3 The comparison of the economies and costs at different plants, such that the manufacture of articles requiring a greater or less amount of different services may be handled at the most advantageous point whenever this might be a determining feature.

Sufficient engineering data are accordingly necessary to indicate the reason for current performance data and to further show wherein improvements may be possible, as well as to determine the basis upon which the expenses shall be allocated to the various services. However, in addition to this it is of great value to record other engineering items from the following standpoints:

(*a*) In noting the trend in consumption and economies of services with a view toward anticipating future requirements as to capacity, replacement, purchases of services, etc.

(*b*) The data are useful in the design and layout of new factories and extensions.

(*c*) They are of value in connection with various statistical correlations of both a general and special nature.

With a departmental system of manufacturing organization, and with each department endeavoring to reduce its costs to a minimum, a blanket method of billing the power, heat, and light services in proportion to purely arbitrary standards has been found undesirable, as no department manager is willing to accept the charges for a blanket distribution of services unless he feels that he is using such a proportion of these services, and if he should happen to feel that he is using relatively more steam and less power, and that the steam cost is less than the power cost, he is only too anxious to see that he is billed separately for the two individual services. Accordingly, whereas for a small company the liquidation of the entire expenses for these services might at times best be taken care of by a blanket distribution against the entire product, in a highly specialized manufacturing industry, with large plants and each operating with several departments, such a system is not satisfactory. It has accordingly been found that a more satisfactory process is to deal with each of the services independently in so far as possible, and to determine, accordingly, the respective costs of power, steam, compressed air, etc. There is still, of necessity, a certain amount of arbitrariness in the liquidation of these expenses, after the costs are once determined, nevertheless the endeavor is made to determine the costs of the individual services on as accurate a basis as is consistent with a reasonable expense and the limitations of our present accounting facilities.

With a view toward meeting from time to time these fundamental requirements and deriving many additional benefits from a more complete system of reports and records, there has slowly been developed a procedure for power-station accounting, which, though not presented as a panacea for all ills nor as even suitable for all manufacturers, has proved by actual experience more or less satisfactory and has been employed with only minor modifications for over three years in some seven factory plants.

Basis of System

The first fundamental division of accounts in this system is that of segregating the boiler room and boiler-room expenses from all other services, in order to ascertain as accurately as possible the cost of steam. The boiler house is accordingly carried as a separate, individual plant and in effect, sells steam, at cost, to each of the other services, such, for example, as to electric power, to the manufacturing and industrial departments, to the heating system, and to other services. No interdepartmental profit of any kind is made on these transactions, but the boiler-room costs are segregated, the total and unit costs of steam determined for the corresponding output, and these costs are allocated to the respective services each month in proportion to their consumption. Although a factor representing demand is sometimes included in the ultimate liquidation of the expenses of these services, the cost of the individual services are determined exclusively on a consumption basis. In this way the steam charges for each service are prorated and added to the other charges, properly allocated to the individual services, so that a total cost for each service is ascertained. The unit costs are also ascertained wherever practicable.

As the steam item is hence a fundamental one in all these charges, it is essential that a fairly accurate system of determining its cost and distribution is desirable. Fuel being usually the principal element in the cost of steam, all values as to distribution and allocation of cost have been referred to a heat basis, although instead of expressing the different quantities in terms of a conventional heat unit, such as the B.t.u. or million B.t.u., the actual heat values have been divided by 970.4 and the results hence expressed in the equivalent of "Steam from and at 212 deg. fahr."

The adoption of this unit in expressing results is to a certain extent a matter of compromise, the idea being to make all determinations and to allocate the different charges for consumption

[1] Construction Engineering Department, General Electric Co.

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Be sure to bring this copy with you to the Annual Meeting

ENGINEERS REPORT OF POWER STATIONS

C WORKS

Station _____ 5 Weeks ending _____

STEAM GENERATION AND DISTRIBUTION

	DISTRIBUTION	ACTUAL 1000 LB. STEAM BY WEIGHT			1000 LB. STEAM FROM AND TO 212 DEG. F.			Maximum demand per hour
		High Pressure Condensing	High Pressure Non-condensing	Low Pressure Condensing	Total debit above Normal condensate temperature	Credit Exhaust steam returned	Net consumption	
	ELECTRIC POWER (A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
1	Turbine or Engine No. 1	700			850		850	10
2	Turbine or Engine No. 2		55 020		66 650	61 100	5 550	100
3	Turbine or Engine No. 3							
4	Turbine or Engine No. 4	3 000		1 500	5 350		5 350	30
5	Turbine or Engine No. 5							
6	Turbine or Engine No. 6	1 000	6 980		9 690	7 740	1 950	40
7	Auxiliaries							
8	Auxiliaries		1 500		1 820	1 710	110	
9	Auxiliaries							
10	TOTAL	4 700	63 500		84 360	70 550	13 810	180
	WATER SUPPLY & FIRE SERVICE							
11	Fire pumps	360			440		440	
12	Supply pumps	170			210		210	
13	TOTAL	530			650		650	10
	INDUSTRIAL STEAM							
14	Line 1	19 830			24 020		24 020	35
15	Line 2							
16	Line 3							
17	Line 4							
18	TOTAL	19 830			24 020		24 020	35
	TESTING STEAM							
19	Line 1	4 520			5 470		5 470	35
20	Line 2							
21	Line 3							
22	TOTAL	4 520			5 470		5 470	35
	COMPRESSED AIR							
23	Compressor No. 1							
24	Compressor No. 2							
25	Compressor No. 3							
26	Compressor No. 4							
27	TOTAL							
	HEATING STEAM							
28	Line 1	13 270			16 080		16 080	60
29	Line 2	1 940			2 350		2 350	30
30	Line 3			59 500	66 360		66 360	
31	Line 4							
32	TOTAL	15 210		59 500	84 790		84 790	90
	HEATING—HOT WATER							
33	Heating							
34	Pumps							
35	TOTAL							
	HOT WATER LAVATORY							
36	Heating							
37	Pumps							
38	TOTAL							
39	TOTAL NET DISTRIBUTED	44 790	63 500	61 000	199 290	70 550	128 740	350
40	MAX. SIMULTANEOUS DEMAND							250
	BOILER ROOM AUXILIARIES							
41	Feed pumps and cleaners		3 700		4 480	4 260	220	
42	Stokers, Blowers, etc	70	1 500		1 900	1 730	170	
43	TOTAL	70	5 200		6 380	5 990	390	
44	FEED HEATERS			8 550	9 200	650	8 550	

according to a heat basis, and yet to correlate these quantities with the unit more frequently used, namely, 1000 lb. of steam, as such is to a certain extent more easily visualized and is regarded by some as a more tangible quantity than a million B.t.u.

The determination of these basic engineering quantities, such as the heat consumption of the respective services for which steam is supplied, as well as the data of efficiencies, losses, etc., for not only steam, but also for electric power and other services, is ac-

STEAM PRODUCTION

		1000 lb. charged	Percent	1000 LB. STEAM F AND A 212 DEG. F. Debit	Credit
45	Average pressure 208 lb. guage Superheat 142 deg. F. Factor of evaporation 1.139 Debit factor 1.211				
46	Total water fed to boilers	114 650			
47	Blow down	1 090			
48					
49	Steam produced—net feed	113 560		129 200	
50	Boiler room auxiliaries				390
51	Waste exhaust steam				
52	General condensation				50
53	Unaccounted for and meter inaccuracies				20
54	Net steam output		99.6		128 740
55	BALANCE	113 560	100.0	129 200	129 200

FUEL CONSUMPTION

		HEAT VALUE Dry	HEAT VALUE As fired	Service	Banking Hp—Hrs.	Tons used PH Record	Car weight Tons used	Million Btu.
56	Banking boilers							
57	Banking boilers							
58	Banking boilers							
59	Total	13 610	13 490	General	400 000	100		2 722
60	Steam production fuel							
61	Steam production fuel							
62	Total	13 610	13 490	General		6 276		170 578
63	Oil used—gallons							
64	Gas used—million cubic feet							
65	Total							
66	GRAND TOTAL FUEL CONSUMP					6 376		173 300

PLANT DATA

67	Total square feet floor space 2 363 500	71	Number of employees 4 301
68	Percent manufacturing capacity 60	72	Percent overtime
69		73	
70		74	

ELECTRIC POWER GENERATED

		Condensing	Non-Cond.	Low Press.	High tension 11000 Volts	Low tension 600 Volts	Dir. current Volts	Total
75	Generator No. 1	38 000			38 000			38 000
76	Generator No. 2		1 633 300			1 633 300		1 633 300
77	Generator No. 3							
78	Generator No. 4	200 000		50 000		250 000		250 000
79	Generator No. 5							
80	Generator No. 6	50 000	184 200			234 200		234 200
81	TOTAL	288 000	1 817 500	50 000	38 000	2 079 500		2 117 500
82	Power for Turbine room auxiliaries					15 100		15 100
83	Motor-generator exciters					20 500		20 500
84	Other auxiliaries					12 000		12 000
85	Lighting					3 500		3 500
86	TOTAL					51 100		51 100
87	Net Kw-hrs. generated at station				38 000	2 018 400		2 056 400

88 Net Kw-hrs. in percent of gross Kw-hrs. generated 97.2%

cordingly placed under the supervision of the plant engineer, and an engineering report embodying these results and so much of the detailed calculations as should indicate the method of arriving at these results and the reasons for them is accordingly prepared each month by the power-station force.

ENGINEER'S REPORT

The Engineer's Report of Power Stations is accordingly made out for each accounting month, namely, for a four- or five-week period, depending upon whether the particular time interval under consideration has been grouped into a four- or five-week month for purposes of accounting. In it the various services requiring steam are given on the first page in some 44 items, as will be noted from the example included, and the various columns are filled in for the particular service or machine in question from actual meter readings and calculations based upon these meter readings. The actual 1000 lb. weight of steam, as indicated by the various meters, or estimated where such meters are not available, are given in columns B, C, and D, whereas in columns E, F, and G are recorded the calculated debits, credits, and net consumptions expressed on a relative thermal basis in terms of "Steam from and at 212 deg. fahr." In these latter columns an ordinary debit and credit system is employed in such a fashion that the difference between the debits and the credits for any individual machine or service

ELECTRIC POWER GENERATED, PURCHASED AND CONSOLIDATED

		Maximum demand kv-a	Power factor	KILOWATT HOURS				
				High tension 11000 Volts	High tension Volts	Low tension 600 Volts	Dir. current Volts	Total
89	Generated	6 500		38 000		2 018 400		2 056 400
90	Generated							
91	Purchased	2 900		387 100				387 100
92	Purchased							
93	TOTAL	9 400	85%	425 100		2 018 400		2 443 500
94	Maximum simultaneous demand	9 200						

NET POWER FOR DISTRIBUTION

		GROSS KW-HRS. INPUT				NET KW-HRS RELEASED		Losses kw-hrs.
		High tension 11000 Volts	High tension Volts	Low tension 600 Volts	Dir. current Volts	High tension 11000 Volts	Low tension 600 Volts	
95	Transformations	38 000		2 018 400		1 511 610	519 990	24 800
96	Conversions							
97	Line losses	387 100				386 590		510
98	Unaccounted for					1 500		1 500
99	TOTAL	425 100		2 018 400		1 896 700	519 990	26 810

		Dir. current	High tension	Low tension	Total
100	Net power available		1 896 700	519 990	2 416 690

ELECTRIC POWER DISTRIBUTION

		Maximum demand kv-a	KILOWATT HOURS			Total kw-hrs.
			High tension 11000 Volts	Low tension Volts	Dir. current Volts	
101	Feeder 1	1 640	459 100			459 100
102	Feeder 2	1 710	317 950			317 950
103	Feeder 3	2 120	401 200			401 200
104	Feeder 4	1 720	147 000			147 000
105	Feeder 5	300	7 700			7 700
106	Feered 6	700	33 500	84 8630		282 130
107	Feeder 7	500	64 000			64 000
108	Feeder 8					
109	Feeder 9	80		13 200		13 200
110	Feeder 10	20		4 600		4 600
111	Total Factory	8 840	1 430 450	266 430		1 696 880
112	Boiler room auxiliaries	70		47 560		47 560
113	Hot water (Heating)					
114	Hot water (Lavatory)					
115	Refrigerated water	250		135 560		135 560
116	Compressed air	800	415 850			415 850
117	General water supply	120		70 440		70 440
118	Testing	1 640	50 400			50 400
119	Testing					
120	Total Testing					
121	Power sold					
122	Power sold					
123	Total Power Sold					
124	GRAND TOTAL OF ABOVE ITEMS	11 720	1 896 700	519 900		2 416 690
125						
126						
127						

represents the net consumption of that particular machine or service.

The fundamental thermal data for the determination of these debits and credits are derived principally from the total heat of the steam supplied as measured above the general condensate temperature, that is, above the average temperature at which the drips, make-up, and condensate are returned to the system before being heated in the feedwater heater. By using this average temperature of condensate and returns as the base above from which all debits and credits are computed, it is true that no account is taken of the minor differences in heat consumption due to the various services returning condensate and drips at other than the general condensate temperature, but it was felt that to record the temperature of returns from each of the various services was a refinement not warranted at the present time. For example, if the service of "Electric Power" returned its condensate to the system at 90 deg. fahr., whereas the returns from the "Heating" services were 160 deg. fahr., making the average, let us say, 120 deg. fahr., the difference in heat consumption for the condensate between 120 deg. fahr. and the 90 deg. fahr. would not be charged to electric power, nor would the credit between 150 deg. and 120 deg. for the heating returns be given to that service but each would be debited and credited as if each had returned its condensate at 120 deg. fahr. By such a procedure the overcharge or undercharge is not large and the various debits, credits, and consumptions for the individual services are approximately in proportion to their true heat values.

STATION STATISTICS

	STEAM	PREVIOUS MONTHS OPERATION				This month
128		Nov.	Dec.	Jan.	Feb.	March
129	Total net steam f. and a. 212 deg F.—million lb.	88.2	137.7	126.5	113.8	128.7
130	Net steam in percent of gross steam	99.6	99.6	99.7	99.7	99.6
131	Boiler capacity factor	68.0	85.0	97.5	88.0	79.4
132	Boiler load factor	159	160	167	156	158
133	Thermal efficiency boiler room (including banking)	68.7	74.4	76.	73.9	72.0
134	Thermal efficiency boiler room (excluding banking)	69.3	75.5	76.5	74.7	73.2
135	Boiler efficiency (including banking)	69.0	74.7	76.2	74.2	72.5
136	Percent make up to total feed	34.0	27.0	27.0	25.2	29.7
137	Average feed temperature Deg. F.	202	208	210	212	209
138	Average make up temperature Deg .F.	66	55	61	66	89
139	General condensate temperature Deg. F.	130	136	134	139	136
140	Temperature in condenser hot wells Deg. F.	76	74	63	64	70
141	Average cooling water temperature Deg. F.	64	61	51	56	61
142	Average vacuum maintained inches hg.	28.9	28.8	29.1	28.9	29.04
143	Comb in Aah.	26.2	19.4	20.2	25.2	18.9
	ELECTRIC POWER					
144	Thousands net kw-hrs. per month	1427	2011	1865.5	1749	2056
145	Generator capacity factor	29	32.6	38	35.6	33.7
146	Load factor	34.2	38.7	44.7	41.3	44.2
147	Power factor	85	85	85	85	85
148	Thermal efficiency generated power	25	37	39.4	41.1	37.6
149	Pounds of coal per kw-hr.	1.02	0.674	0.627	0.612	0.668
150	Total power house interruptions minutes	0	0	0	2	4
151	kw-hrs. per 1000 lb. steam—Unit No. 1					44.7
152	kw-hrs. per 1000 lb. steam—Unit No. 2					294
153	kw-hrs. per 1000 lb. steam—Unit No. 3					
154	kw-hrs. per 1000 lbs. steam—Unit No. 4					46.7
155	kw-hrs. per 1000 lbs. steam—Unit No. 5					
156	kw-hrs. per 1000 lbs. steam—Unit No. 6					120
157	kw-hrs. per 1000 lbs. steam—Station	105	142.5	152	160.1	148.5

COMPRESSED AIR

		Delivery cubic feet	Max hourly demand—cu. ft.	kw-hrs. consumed	1000 lb. steam from & at 212 deg. F.	Performance
158	Compressor No. 1	55 760 000		160 720		
159	Compressor No. 2	12 250 000		35 300		
160	Compressor No. 3	55 400 000		159 560		
161	Compressor No. 4	12 880 000		37 170		
162	Compressor No. 5	8 020 000		23 100		
163	Compressor No. 6					
164	TOTAL	144 310 000	470 000	415 850		347 Cu.ft. per KWhr.

WATER

		CONSUMPTION GALLONS			MAX. HOURLY DEMAND AND GALLONS OR CUBIC FEET		
		City water	Works water	Total	City water	Works water	Total
165	Steam production	9 940 000		9 940 000			
166	Electric power production	5 500 000		5 500 000			
167	Hot water heating						
168	Refrigerated water		580 000	580 000			
169	Compressed air		2 120 000	2 120 000			
170	Miscellaneous uses		36 860 000	36 860 000			
171							
172	TOTAL	15 440 000	39 560 000	55 000 000			
173	Maximum simultaneous demand						

But as some services take high-pressure steam and return low-pressure steam to the system, such for example as non-condensing and extracting turbines, it is necessary to credit these returns in such a fashion that the particular service considered is not charged with more than a fair share of the heat in the steam. For such a service, the debits are computed as before, but in this case the heat content of the returned steam is either estimated, or calculated, above the same general condensate temperature and a credit, representative of the heat returned, is entered for the particular service. The difference then between these debits and these credits, appearing respectively in columns E and F, represents the net consumption for the particular service, expressed in terms of "Steam from and at 212 deg. fahr." For a non-condensing turbine, practically speaking, the only heat consumption

C 5

(based on net output)		Amount
6376	356 NT	22 700 00
9 940 000 Gals.		500 00
47560 KWH		420 00
		725 00
		1 700 00
		425 00
		50 00
		40 00
Other operating labor		310 00
Lubricants and waste		340 00
Misc. operating expense		380 00
Maint. of Buildings		20 00
" " Boilers and accessories		150 00
" " Stacks and flues		
" " Stokers and grates		900 00
" " Boiler room auxiliaries		250 00
" " Conveyors		30 00
" " Piping		175 00
" " Misc. repairs		100 00
Group Insurance		15 00
Depreciation		5 200 00
Supplementary Group		150 00
Taxes		400 00
Insurance		25 00
Factory assessment		125 00
Total		35 130 00 .2730

DISTRIBUTION OF STEAM PRODUCED

	Pounds	Amount	Pounds	Amount	Pounds	Amount
For electric current	13810000	3780 00				
Pumps or fire and water supply	650000	175 00				
Manufacturing steam	24020000	6560 00				
Testing steam	5470000	1460 00				
Other						
Heating steam live	18430000	5035 00				
" exhaust	66360000	18100 00				
" hot water						
Compressed air						
Total	128740000	35130 00				

COST OF STEAM FOR HEATING

	Without interest	With interest
Live steam station	5 035 00	
" " "		
Exhaust steam "	18 100 00	
" "		
Total	23 135 00	

INTEREST BASIS

Interest computed at 6% on investment including land, buildings and equipment as follows

	Boiler room	Engine room
Station		

		Station		Total	
	Amount	Cost per Kw-hr	Amount	Cost per Kw-hr	Amount	Cost per Kw-hr
13 810 000	3 780 00					
5 500 000 Gals.	275 00					
	500 00					
	200 00					
	800 00					
	450 00					
	175 00					
	40 00					
	30 00					
	1 500 00					
	500 00					
	75 00					
	300 00					
	75 00					
Group Insurance	25 00					
	4 500 00					
Supplementary Group	125 00					
	375 00					
	40 00					
	150 00					
	14 015 00	.00691				

ELECTRIC POWER CONSOLIDATION (STEAM AND PURCHASED POWER)

Source	Kw-Hrs	Without interest		With interest	
		Rate	Amount	Rate	Amount
Less Losses	2 029 590	.00691	14 015 00		
Purchased	387 100		7 300 00		
	2 416 690	.00883	21 315 00		

DISTRIBUTION OF ELECTRIC CURRENT

Sold to					
Factory service	1 882 840	.00883	16 610 00		
Station auxiliaries	47 560	.00883	420 00		
Industrial water	70 440	.00883	620 00		
Heating (hot water)					
Compressed air	415 850	.00883	3 665 00		
	2 416 690	.00883	21 315 00		

is that resulting from the thermal equivalent of the electric power output, corrected for such losses as there may be in the turbine and the generator. Accordingly the rest of the heat, in this particular cast, is credited to the particular service, leaving only a small net consumption wherever the exhaust steam is ordinarily available for some other purpose. In the event, however, that the turbine is a non-condensing machine but there is ordinarily no use for the exhaust steam, and none can be made available, the entire amount of heat is charged against the particular machine. The determination of these debits, credits, and net consumptions for electric power is more difficult than for any of the other services, as this service involves so many different combinations; for examples, steam for straight condensing purposes, for non-condensing machines, for extraction and low-pressure machines. Hence the hypothetical figures shown in the sample report have been chosen as arbitrary examples and calculated in detail under "Instructions and Explanations of Engineer's Report" merely as an illustration of the method of computing the various items.

It will be noted from this report that the Total Net Steam Distributed is considered merely as that total which is distributed for useful purposes. In other words, it does not include the boiler-room auxiliaries nor any of the boiler-room losses, as these are otherwise accounted for. The Total Net Distributed, as indicated in item 39, is furthermore the figure used for the determination of all costs and for the allocation of the expenses to the individual services requiring steam.

The feedwater heaters obviously should not appear in the steam balance proper, due to the fact that although they consume steam in heating the feedwater, all of the heat is returned to the system, and therefore it must necessarily have no net consumption for which fuel is required. The item is calculated in such a fashion as to illustrate the consumption of steam in the feedwater heater, but the total consumption therein indicated is not used in any of the tabulations making up the distribution of steam, or in the balance tabulations.

Another tabulation under the heading Steam Production illustrates the method used in further accounting for the steam generated. The Net Steam Output, as in item 54, is the same as that previously determined in item 39, and the difference between the Steam Produced—Net Feed, and the Net Output is represented by the various items such as Steam for Auxiliaries, Waste Steam, and General Condensation, all of which are individually estimated and the remaining item of Unaccounted For and Meter Inaccuracies, which is introduced to complete the balance.

In addition to each of the above tabulations there is included in the report a table on Fuel Consumption, the various columns of which are devoted to the different services in connection with which fuel is used. At first, it was endeavored to segregate the coal used in banking boilers and charge it to the individual services, but this was soon found to be an unnecessary refinement and complication and hence is not now done, although the items are still retained on the report. The heating value of the fuel used in the various computations as to overall efficiencies, etc., is the dry heating value. It is to be noted that this is not a truly representative figure, and that by its use each plant is charged with somewhat more heat than is proper, but in view of the difficulty of determining the true heating value of the coal as fired, especially where the analyses are sometimes made at a different plant from that in which the coal is burned, it has been felt that the injustice by charging each plant with the dry heating value is probably distributed more or less equally in the long run and offers the distinct advantage of simplicity.

Furthermore in the Engineer's Report, a few items on general plant data are included to indicate certain features by which the power and steam consumptions can be correlated with manufacturing activities. The study of these correlations has been a most interesting subject and has led to a knowledge of the growth of power in manufacturing and its increasing use per employee, which has been of a great interest, as well as being of value in the determination of probable quantities to be expected in new plants and extensions.

The electric power generated has also been segregated into several classifications, namely, as to condensing, non-condensing, and low-pressure methods of generation as well as by classification according to voltage. In addition to this, something of a debit and credit system has been employed in the tabulation under net power for distribution, such indicating the losses sustained in transforming and converting the power from the form in which it is generated to the form in which it is distributed. The distribution of electric power is likewise indicated in a tabulation in this report.

In addition to these values, a set of station statistics is tabulated each month, such tabulation also containing a record of similar data for the preceding four months. These consist of general figures such as the thermal efficiencies of the boiler room, the boiler capacity factors and the average temperatures of the cooling water, vacuum, etc., and are recorded to give in a general way a rough comparison of the general features, indicative of plant performance for the current month and its relation to the operation during the previous months.

Data for the services of compressed air and water are also included in the engineer's report. The consumption or delivery and the power used being recorded wherever these items are available.

Although the Engineer's Report contains some 173 different items and is a somewhat formidable looking document when first reviewed, most of the data contained in it are those which would ordinarily be required for the successful operation of any power plant where the various services must be segregated. This report is now one of the basic elements in the system of accounts and records used in some seven of the General Electric Company's plants. It has not, however, been adopted by all of the various factories. As a general proposition, it has been found that in converting from the old system to this system, a certain number of extra calculations have of necessity been required, as well as the installation of additional meters in certain of the plants, but after the system has been installed, it has also been found that the time required to prepare the report has not been excessive and we are advised by certain of the power-plant superintendents that the preparation of these reports entails little more difficulty than the previous accounting system which was by no means so complete. It requires only a knowledge of the station and a reasonable familiarity with the use of the ordinary steam tables.

Accountant's Report

In addition to the engineer's report previously described, another report is prepared by the Accounting Department, such report containing the record of costs and expenses and the distribution of them to the various services. These costs are classified by the Accounting Department under various headings, such as the cost of coal, the cost of water, labor for different services, maintenance depreciation, group insurance, taxes, factory assessments, etc., and are tabulated for the individual services, such as for the boiler room and turbine room. In this way the steam charges are first determined and the allocation of the steam costs to the various services, such as to electric power, to manufacturing steam and to other services, is then effected according to the distribution prepared by the plant engineer and indicated in the Engineer's Report. An example of the Accountant's Report known as the Report of Power Stations has also been included for a period comparable to that of the Engineer's Report, the data for both being hypothetical and merely illustrative. Probably the only unusual element about the Accountant's Report is the fact that no interest is ordinarily included in the determination of these particular costs. This has the advantage that it can be handled separately as a financial operation, thus simplifying the accounting and further avoiding the argument as to what rate should be used. It should also be noted that the minor services, such as compressed air and water are not recorded completely on this report, although the charges to these services in the way of power and steam requirements, are indicated.

Comparison Report

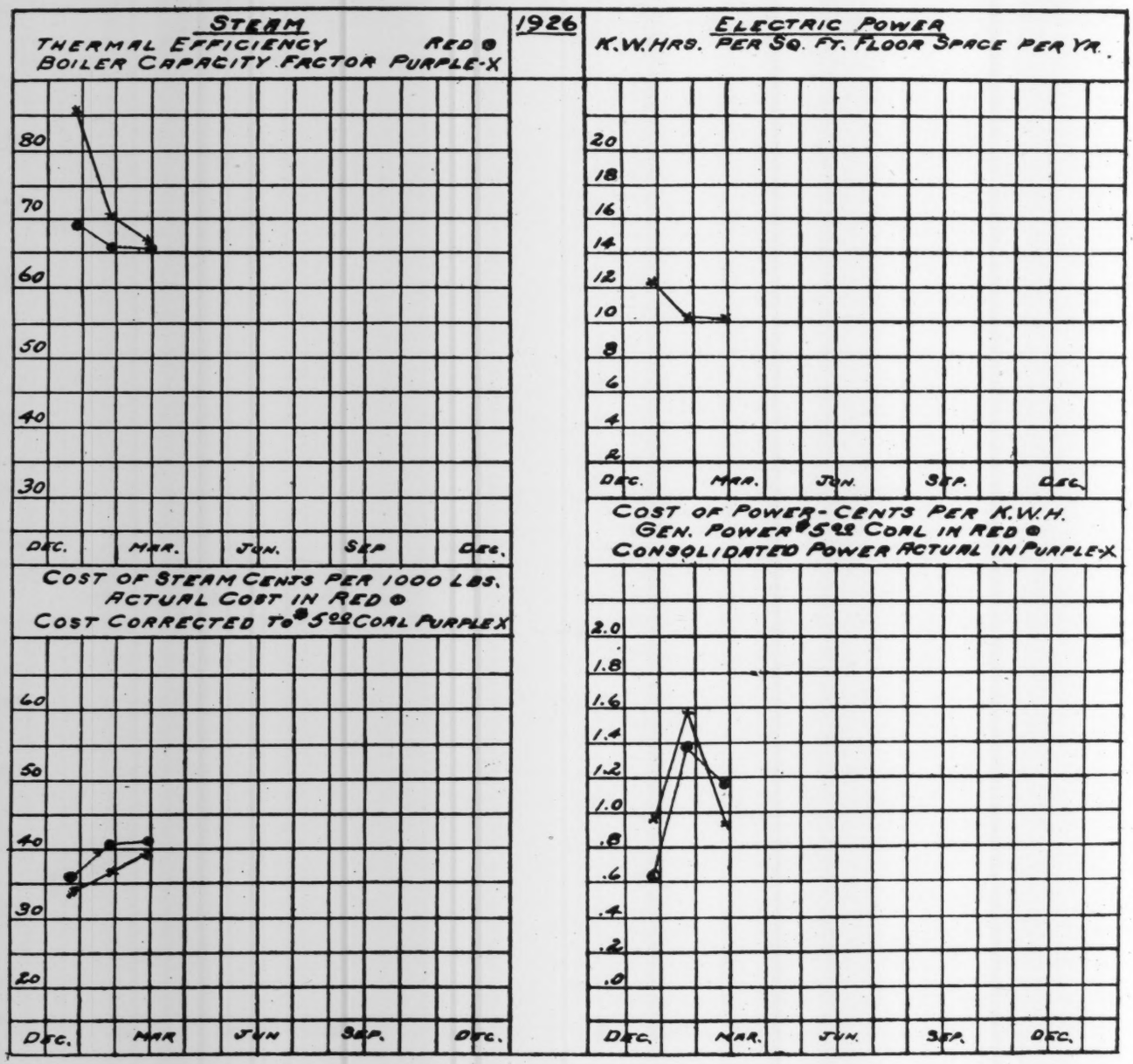
The Engineer's Report and the Accountant's Report are of interest primarily to the particular factory in question, and their distribution is principally to those members of the individual organizations who are responsible for the operation of the plant, or who are otherwise interested in its economy. A copy however,

GO-618 100 12-17-25

COMPARISON REPORT OF G. E. POWER STATIONS

5 Weeks ending Year

	STATION OR WORKS									
(Steam 1. & a. 212 ° F)	A	B	C	D	E	F	G	H	I	
STEAM PRODUCTION										
1 Average pressure gauge ....lb.			208							
2 Superheat .....Deg. F.			142							
3 Feed temperature .....Deg. F.			209							
4 Gen. condensate temp. Deg. F.			136							
5 Make-up in percent total feed ..			29.7							
6 Temp. cooling water ..Deg. F.			61							
7 Total net steam (1000) lb.			128740							
8 Net steam in percent gross			99.64							
9 Boiler capacity factor .....%			79.4							
10 Boiler load factor .....%			158							
11 Efficiency boiler room . . .%			72.0							
12 Heat value coal....Btu. per lb.			13610							
13 Heat value oil....,Btu. per lb.										
14 Total coal consumed Net Tons			6376							
15 Total oil consumed ....Gallons										
16 Total million Btu. in fuel			173300							
STEAM COSTS										
17 Cost of coal per ton .....$			3.56							
18 Cost of oil per 1000 gal. .....$										
19 Total cost of fuel .....$			22700.00							
20 Water, auxiliaries etc. .....$			920.00							
21 Labor .....$			3250.00							
22 Miscl. operating expense ....$			720.00							
23 Maintenance .....$			1625.00							
24 Depreciation .....$			5200.00							
25 Fixed charges $			715.00							
26 Total cost steam gen.(excl.int.)$			35130.00							
27 Cost per 1000 lb. net steam ..$			.2730							
28 Cst per 1000 lb. steam ($5 coal)$			.3465							
ELECTRIC POWER PRODUCTION										
29 Maximum demand K. V. A.			9200							
30 Thousands Net KW hr gen.			2056.4							
31 Net KW-hr. in % KW-hr. gen...			97.2							
32 Generator capacity factor ..%			33.7							
33 Generator load factor .....%			44.2							
34 Average power factor			85							
35 Purchased power 1000 KW-hr. ..			367.1							
36 Power sold 1000 KW-hr.			-							
37 Total net consl. power			2416.7							
38 Total net 1000 lb. steam to pwr.			13810							
39 KW-hr. gen. cond. per 1000 lb..			50.5							
40 KW-hr. gen. noncond. per 1000 lb.			288							
41 Net KW-hr. gen. per 1000 lb....			148.5							
RATE OF CONSUMP. POWER										
42 Volt-Amps. dem. per sq. ft. space			3.89							
43 KW-hr. per yr. per sq. ft. space .			10.6							
44 1000 KW-hr.net per emp. per yr.			5.68							
ELECTRIC POWER COSTS										
45 Cost of steam to power .....$			3780.00							
46 Water, auxiliaries, etc. .....$			275.00							
47 Labor .....$			1950.00							
48 Miscl. operating expense ....$			215.00							
49 Maintenance .....$			2580.00							
50 Depreciation .....$			4500.00							
51 Fixed charges $			715.00							
52 Total cost pwr. gen.(excl. int.)$			14015.00							
53 Cost per KW-hr. pwr. gen. ..$			.684							
54 Cost per KW-hr. gen.($5 coal) .$			.732							
55 Total cost pwr. gen. and pur..$			21315.00							
56 Cost per KW-hr. consol. pwr...$			.883							
57										
COMPRESSED AIR										
58 Total delivery million cu. ft. ...			144,310							
59 Total cost ... ...$			5500.00							
60 Cost per million cu. ft. .....$			38.10							
PLANT STATISTICS										
61 Square feet floor space			2363476							
62 Number of employees			4301							



CURVES SHOWING AVERAGE EFFICIENCIES AND UNIT COSTS
(The curves through the large black dots are those referred to in the text as being indicated in red.)

of each of these reports is further sent to a central office which makes up from the individual engineers' reports and accountant's reports at the several plants a Comparison Report of Power Stations, an example of which is also included. Its purpose is to show the relative costs and operating performances at the various plants computed on a comparable basis, and hence it contains in addition to the cost data, such general information as to operating records as will give in a brief way a general idea of the efficiencies and principal conditions leading to such costs.

However, as the cost of fuel varies at the different stations and as the equipment is different at the various plants, the comparison is made in each of two ways:

(1) On the basis of the actual costs obtaining as reported by the Accounting Department's figures, and

(2) On otherwise this same basis but with a correction for the cost of coal, such that each plant is charged in its fuel cost as if it has bought the thermal equivalent of its consumption in terms of coal at five dollars per net ton, each pound having 13,500 B.t.u. In this way, with the cost of fuel corrected to a standard base of five dollars for 27,000,000 B.t.u., the steam and power costs should be approximately representative of the relative performances of the various stations, on a more or less comparable basis.

In this Comparison Report the various cost elements have been grouped for convenience into slightly larger divisions than indicated on the Accounting Department's report, but otherwise they are representative of the same expenditures.

Such important items as the efficiencies and the unit costs are furthermore averaged for all of the stations and a curve is drawn of the average of these values, such curve being shown each month on the back page of the report. For the particular plants at which poorer than average performance has been obtained during any month, the corresponding figures are usually indicated in red. These plants which happen to be above the average have their corresponding figures in purple. In this way attention is immediately drawn to such plants as are below or above the average in their operating performances or unit costs.

CONCLUSION

The above three reports accordingly constitute the principal records of the operating economies of the various power stations considered. They meet most of the desired characteristics as

previously outlined and represent a rather complete record of the operating data at each of the stations for the month considered.

The Engineer's Report and the Accountant's Report, as may be noted from a perusal of their items, in a fair way satisfy the first two desiderata of power-station accounts, namely, first to be illustrative of the economy of operation with a view toward indicating where betterment may be possible, and secondly, to be illustrative of a reasonably proper distribution of expenses among the various services. The Comparison Report meets the third feature desired, namely, to be illustrative of a more or less accurate comparison of economies and costs at the various stations and factories. The three reports contain sufficient information to illustrate the cause of any ordinary discrepancy resulting from operation and hence offer the opportunity to the power-station operators of locating any anomaly and correcting it, while the Comparison Report further serves as a stimulus for those plants which are below average to take the initiative and to improve their operating performances and economies and bring up their own average. In this probably lies its greatest value, as a certain average improvement has been noticed in the plants where this system has been installed, although of course it is impossible to assign this improvement dogmatically to any one cause. However, it is felt that the savings effected by this competitive effort have more than compensated for any complications in the way of retaining the three reports.

Instructions for Explanation of Engineer's Report Form Sheet FF-392-A

SECTION I STEAM GENERATION AND DISTRIBUTION

USE OF COLUMNS

Column A—This column should be used for the designation of the machine or service considered.

Column B—This column should be used for the entry of steam quantities for any machine or service using *high-pressure steam* and *not returning steam* at a lower pressure. Metered or estimated quantities in actual 1000 lb. weight of steam should here be recorded as a charge against the machine or service.

Column C—This column should be used for the entry of steam quantities for any machine or service using *high-pressure steam* but *returning steam* to the system at a lower pressure. Metered or estimated quantities in actual 1000 lb. weight of steam should here be recorded as a charge against the machine or service.

Column D—This column should be used for the entry of steam quantities for any machine or service utilizing *low-pressure steam* and *condensing or not returning it as steam*. Metered or estimated quantities in actual 1000 lb. weight of steam should here be recorded as a charge against the machine or service.

Column E—This column should be used as a *debit column* and in it should be entered *debits calculated* from the quantities in columns B, C, and D in terms of "steam from and at 212 deg. fahr.," such being figured from the heat in the steam above the average temperature of all the returned condensate and make-up before being heated to feed temperature (i.e., above the *general condensate temperature. Item 139.*)

Column F—This column should be used as a *credit column* and in it should be entered *credits* for any service or machine which returns *low-pressure steam* to the system, such *credits* being expressed in terms of equivalent "steam from and at 212 deg. fahr," calculated from the heat value of the returned steam as measured above the *general condensate temperature.*

Column G—In this column should be entered the difference between the *debits* and *credits*, that is, the difference between columns E and F, and hence represents the *net consumption* expressed in terms of equivalent "steam from and at 212 deg. fahr."

Column H—In this column should be recorded the maximum *demand* during any 10-minute period expressed as an hourly flow rate in terms of 1000 lb. actual weight of steam per hour.

USE OF ITEMS

Record the various quantities in the correct columns for the machines or service considered.

Items 1–6

EXAMPLE: (*a*) High-Pressure Condensing Turbine, Unit No. 1.
Steam pressure 208 lb. gage, 142 deg. fahr. superheat. (Item 45.)
General condensate temperature, 136 deg. fahr. (Item 139.)

Total heat in steam above 32 deg. fahr	1284.6 B.t.u.
Heat liquid general condensate 136 deg. fahr	104.0 B.t.u.
Heat above general condensate temperature	1180.6 B.t.u.

To express this heat in terms of equivalent steam from and at 212 deg. fahr., divide by 970.4. Hence *debit factor* (Item 45) $= \frac{1180.6}{970.4} = 1.211$.

Assume flow-meter reading for actual 1000 lb. condensing = 700. Then *total debit* above condensate temp. = 700 × 1.211 = 850. Hence enter the following quantities in Item 1:

In Col. B, 700; *charge* as weight
In Col. C and D; *no entry*
In Col. E, 850; *total debit F. and A. steam*
In Col. F; *no entry*, as no *steam* was returned
In Col. G, 850; *net consumption F. and A. steam.*

EXAMPLE: (*b*) High-Pressure Non-Condensing Turbine, Unit No. 2. Steam conditions, debit factor, etc., same as in (*a*). (See Item 45.) Flow-meter record of 1000 lb. weight to machine, 55,020. Hence, *debit* equals 55,020 × 1.211 = 66,650. If quality of exhaust is measured, determine a corresponding low-pressure debit factor and *credit* (Col. F) exhaust steam on this basis.

If quality of exhaust is not measured compute as follows:

Let H = total heat h.p. steam above general condensate temperature
A = full-load water rate, lb. per kw-hr. non-cond.
B = half-load water rate, lb. per kw-hr. non-cond.

Then B.t.u. consumption per pound weight of steam is given by following:

$$\text{Consumption} = \frac{3412 + 10 \text{ per cent}}{2A - B} = \frac{3753}{2A - B} \text{ B.t.u. per lb.}$$

(NOTE: If water rate is given in terms of horsepower-hours rather than kw-hr., substitute 2546 in above formula in place of 3412.) Hence per cent of *total debit* which is *net consumption* is $\frac{3753}{H(2A - B)} \times 100$ per cent and the *credit exhaust steam returned* in per cent of the *total debit* is given by

$$\frac{H - \frac{3753}{2A - B}}{H} \times 100 \text{ per cent.}$$

Where $A = 41.2$
$B = 44.0$
$2A - B = 82.4 - 44 = 38.4$

$$\frac{3753 \times 100 \text{ per cent}}{1180.6 \times 38.4} = 8.3 \text{ per cent}$$

If condensate is measured, deduct high-pressure steam flow from total condensate to obtain Col. D entry. For example:

Total condensate	4500	thousand lb. weight
Hp. flow	3000	thousand lb. weight
Col. D entry	1500	thousand lb. weight

To determine portion of debit for low-pressure steam, determine average quality. For example:

Total heat	1210 B.t.u.
Heat liquid gen. condensate	104 B.t.u.
Heat per pound above gen. cond	1106 B.t.u.

$\frac{1106}{970.4} = 1.14$ = debit factor for low-pressure steam.

Hence debit = 1500 × 1.14 = 1710. Credit is zero as no steam returned. Consumption hence same as debit = 1710. Hence total quantities for Item 4 should be—

Col. B, 3000; *charge* as weight
Col. C; *no entry*
Col. D, 1500; *charge low pressure* as weight
Col. E, 3640 + 1710 = 5350; *total debit*
Col. F, *no entry*
Col. G, 3640 + 1710 = 5350; *net consumption*

EXAMPLE: (*c*) Extraction Turbine, Unit No. 6. High-pressure steam conditions, debit factor, etc., same as before (Item 45). Total high-pressure throttle flow from meter reading, say, 7980. Total debit hence = 7980 × 1.211 = 9690. Steam extracted, from meter reading (6980). If

8.3 per cent of 66,650 = 5,550
91.7 per cent of 66,650 = 61,100

Hence the following figures should be entered in Item 2:
In Col. C, 55,020; *charge in as 1000 lb. weight*
In Col. B and D; *no entry*
In Col. E, 66,650; *debit F. and A. steam*
In Col. F, 61,100; *credit exhaust*
In Col. G, 5,550; *net consumption*

EXAMPLE: (*d*) Mixed-Pressure Condensing Turbine, Unit No. 4. High-pressure steam conditions, debit factor, etc., same as before. (See Item 45.) Flow-meter record high-pressure steam, say, 3000 1000-lb. weight. Debit for high-pressure steam, 3000 × 1.211 = 3640. No credit for high-pressure steam. Consumption for high-pressure steam = 3640. For the low-pressure steam, use flow meter record, say, 1500, for column D. In absence of flow meter record for this calculate as follows:

$$\text{Col. D Entry} = \left[\text{Kw-hr. total} - \frac{\text{H.p. Steam flow}}{\text{H.p. Water rate}}\right] \frac{\text{Low-pressure water rate}}{1000}$$

Assume H.p. steam flow 3000 thousand lb.
H.p. water rate = 15 lb. per kw-hr.
H.p. water rate = 30 lb. per kw-hr.
Total kw-hr. = 250,000

$$\text{Col. D entry, } 250{,}000 - \frac{3{,}000{,}000}{15}\,\frac{30}{1000} = 1500$$

Meter reading not available, compute as follows:

$$\text{1000 lb. weight steam extracted} = \frac{S - (WRc \times L)}{1000(WRe - WRc)} \times WRe$$

S = total throttle high-pressure steam flow, say, 7,980,000 lb.
WRc = water rate condensing, say, 20 lb. per kw-hr.
WRe = water rate extraction, say, 38 lb. per kw-hr.
L = total load in kw-hr., say, 234,200.

$$\text{Then steam extracted} = \frac{7{,}980{,}000 - 20 \times 234{,}200}{1000(38 - 20)} \times 38 = 6980.$$ Hence steam high-pressure condensing = (7980 — 6980) = 1000.

To determine the credit for the steam extracted compute as follows, where H = heat of initial steam *above general condensate temperature.*

$$\text{B.t.u. per lb. consumption} = \frac{3412 \div 10\%}{WRc} = \frac{3753}{38} = 99$$

$$\text{Whence consumption} = \frac{\text{Steam extracted} \times 99}{970} = \frac{6980 \times 99}{970} = 710$$

Portion of debit, 6980 × 1.211 =	8450
Consumption.....	710
Whence credit exhaust steam.....	7740

Whence quantities should be entered in Item 6 as:
Col. B, 1000; *charge* as weight h.p. condensing
Col. C, 6980; *charge* as weight h.p. extraction
Col. D; *no entry*
Col. E, 9690; *total debit*
Col. F, 7740; *credit exhaust returned*
Col. G, 1950; *net consumption*

Items 7–9.

It is preferable to meter all steam to turbine-room auxiliaries and to boiler-room auxiliaries in which case the *credit exhaust steam* can be calculated as for non-condensing turbines. If meter records cannot be obtained, the steam flow should be estimated from the number of hours each auxiliary is in service and its prevailing load.

The percentage of the steam chargeable to power when the auxiliary turbine is exhausting into the heating system can be calculated thus; where H is the total heat *above the general condensate temperature:*

$$\frac{1}{H}\left(\frac{2546 \div \phi 10\% = 2800}{\text{Water rate per hp-hr.}}\right) \times 100\%$$ if water rate is on basis of horse power developed by prime mover, or

$$\frac{1}{H}\left(\frac{2546 + \phi 10\% = 2800}{\text{Water rate per hp-hr.} \times 0.50}\right) \times 100\%$$ if water rate is measured over complete set.

For example, if total flow to auxiliaries is 1500 thousand lb. from flow-meter reading and if H = heat above general condensate temperature (1180.6) and with 25½ lb. per hp-hr. water rate and same debit factor, etc.:

$$\frac{2800}{1180.6 - 25.5} \times 100\% = 6.05\%$$

6.05% × 1.211 × 1500 = 110 Net consumption
And credit is 1820 − 110 = 1710. Hence for:
Cols. B and D; *no entry*
Col. C, 1500; h.p. *non-condensing charge*
Col. E, 1820; *total debit*
Col. F, 1710; *credit exhaust steam*
Col. G, 110; *net consumption.*

Items 11–12: Water Supply and Fire Service.

Turbines or engines driving fire or service pumps should be *charged* and *debited* with high-pressure steam and *credited* with exhaust steam, if any is returned to the system, the same as the main non-condensing turbines, otherwise charge same as condensing machines. (See Items 1–6.)

Items 14–17: Industrial Steam.

Industrial steam sent out to the factory will be charged the same as for other condensing services, such as condensing turbines because the returns are not in the form of steam but of water. Calculate the same as for condensing power.

For example: Flow-meter record 19,830,000 actual pounds.

$$\frac{19{,}830{,}000}{1000} \times 1.211 = 24{,}020$$

Hence:
Col. B, 19,830; thousand pounds *charge*
Cols. C and D; *no entry*
Col. E, 24,020; *total debit equivalent steam*
Col. F; *no entry*
Col. G, 24,020; *net consumption.*

Items 19–21: Testing Steam

Testing steam may be condensing or non-condensing and therefore will be *charged* in Col. B or C. If exhaust steam is returned to the system, *credit* should be given in Col. F unless the intermittent or unreliable supply makes it impracticable to utilize it in which case treat as condensing steam. Calculate the same as for turbines (Items 1–6).

Items 23–26: Compressed Air

Steam-driven compressors should be treated similarly to turbo-generators. Calculate same as for Items 1–6 on basis of condensing or non-condensing service as the case may be.

Items 28–31: Heating Steam

High-pressure steam used for heating should be *charged* in Col. B. Low-pressure steam shall be *charged* in Col. D, both being metered or estimated. It is not satisfactory to assume that all exhaust steam goes to the feed-water and to the heating system. Treat these services same as for condensing or mixed-pressure turbines, Items 1–6.

Items 33–34: Heating Hot Water

This group applies to factory plants using the hot-water systems of heating. Treat as condensing service the same as in Items 1–6.

Items 36–37: Hot-Water Lavatory

These items apply to power plants equipped with hot-water heaters for *lavatory service* throughout the factory. Treat as condensing service either high-pressure or low-pressure as in Items 1–6.

Item 39: Total Net Distributed

In Item 39, total the various columns. It should be noted that certain of these totals overlap and represent duplication particularly such columns as D and E, which contain duplications of other items. The total in Col. G represents the net steam use fully employed outside of plant.

Item 40: Maximum Simultaneous Demand

In Item 40, record maximum simultaneous demand for steam. The diversity factor will then be apparent by comparison of this with the total of the individual demands recorded in Item 39.

Items 41–42: Boiler-Room Auxiliaries

These items cover all auxiliary steam consumption incidental to steam production regardless of where such auxiliaries are located. The steam flows *charged* and *net consumptions*, etc., should be obtained in a similar manner to corresponding data for turbine room auxiliaries. See Items 7–9.

Item 44: Feed Heaters

Rather than assume that a heater has consumed all of the exhaust steam from the auxiliaries, the quantity of steam should be estimated from the net amount of water heated and the temperature rise. The object of this is to show the approximate deficiency or excess of exhaust steam so that it can be remedied. The *net feed* quantity (Item 49) is used, as heating any additional over the *net feed* is waste. This method does not give a theoretically accurate result but one which is close enough for general purposes. The *net consumption* is *first* calculated and *from this* the pounds weight of steam computed.

For example:

1000 lb. *steam produced—net feed* (Item 29) — 113,560
Rise of feed (209° F.–136° F.) = 73° F.

$$\text{Million B.t.u. required above 209 deg. fahr., water} = \frac{113{,}560 \times 73}{1000} = 8290.$$

$$\text{Hence equivalent } \textit{net consumption} \text{ is } \frac{8290 \times 1000}{970} = 8550.$$

In absence of determination of steam quality to heater, calculate

total heat of steam f. and a. 212 deg. fahr	970.4
Correction for 209 deg. fahr. temp. (212–209)	3.0
Assumed heat per pound steam above 209 deg. fahr.....	973.4

$$\text{Hence } \frac{8290}{973.4} = 8550 \text{ thousand pounds actual weight } \textit{charge Col. D.}$$ Debit factor heater steam $\frac{970 + 212 - 136}{970.4} = 1.079$. Hence:

Total debit 1.079 × 8520 =	9200
Net consumption	8550
Credit (returns in hot water)	650

Hence:
Col. B and C; *no entry*
Col. D, 8550; *low-pressure steam charge*
Col. E, 9200; *total debit*
Col. F, 650; *credit exhaust*
Col. G, 8550; *net consumption.*

SECTION II STEAM PRODUCTION

Item 45

(*a*) Record in this table operating figures, for example, *average steam pressure* taken directly from gage readings, such, for example, as 208 lb. per sq. in.

(*b*) Average *superheat*, determined by averaging temperature readings, such, for example, as 142 deg. fahr. superheat.

(*c*) *Factor of evaporation*, determined in the usual manner for boiler calculations. For example with the feed temperature 209 deg. fahr. (Item 137.)

Total heat 208 lb. gage 142 deg. fahr.	1284.6 B.t.u.
Heat liq. of feed	177.0 B.t.u.
	1107.6 B.t.u.

Hence factor evaporation $\frac{1107.6}{970.4} = 1.139$

(*d*) The *debit factor* is defined as that factor which multiplied by the pounds weight of steam used, will give a *debit* representative of the heat used above the *general condensate temperature*, but such *debit* instead of being expressed in B.t.u. being expressed in terms of the number of pounds of equivalent steam from and at 212 deg. fahr., in other words B.t.u. divided by 970.4. For example:

Total heat 208 lb., 142 deg. fahr.	1284.6 B.t.u.
Heat liq. gen. cond., 136 deg. fahr.	104.0 B.t.u.
Heat in steam above gen. cond. temp.	1180.6 B.t.u.

Hence *debit factor* $= \frac{1180.6}{970.4} = 1.211$

The purpose of this factor is to determine the various *debits* for the use of steam on a basis representative of actual heat consumption, but instead of expressing the result in terms of actual heat, such as million B.t.u. the heat quantities are divided by 970.4 and hence expressed in so far as the heat is concerned, in terms of pounds of steam from and at 212 deg. fahr., the idea being that the term "1000 pounds of equivalent steam" probably is more expressive and more easily associated with an actual quantity by many individuals reviewing the report than would be the term "Million B.t.u."

Items 46–48

The various quantities should appear in the first column and percentage in second column. The *blowdown* should be estimated, rather than use the difference between the feedwater meter and the boiler-steam flow-meter records. No quantities should be shown in the Debit and Credit columns. For example, water fed to boilers 114,650 thousand lb., Item 46.

Item 49: Steam-Produced—Net Feed

Fill in first column difference between Items 46 and 47. In *debit column* record equivalent steam f. and a. 212 deg. fahr. calculated above the feedwater temperature. For example, 113,560 × 1.139 = 129,200. Do not fill in per cent or credit column for this item.

Item 50: Boiler-Room Auxiliaries

Fill in *credit column*, quantity given in Item 43, Col. G. For example, 390. No entry in *debit column*.

Item 51: Waste Exhaust Steam

Fill in *credit column* estimated excess exhaust steam provided *sum* of Items 39, 43 and 44, Col. F, exceeds the sum of Items 39, 43 and 44, Col. D, multiplied by the average low-pressure debit factor. For example:

	Col. C	Col. F
Item 39	63,500	70,555
Item 43	5,200	5,990
Sum	68,700	76,540

Whence average low-pressure debit factor approx. $\frac{76,540}{68,700} = 1.114$.

And hence:

	Col. D	Col. F
Item 39	61,000	70,550
Item 43	....	5,990
Item 44	8,550	650
Sum	69,550	77,190
Debit factor	1.114	
Whence compare	77,500	77,190

These figures hence indicate a slightly greater *consumption* than *credit exhaust steam*, but the figures check reasonably well and hence no waste exhaust steam. When the total of Col. F exceeds the sum of Col. D multiplied by the average *low-pressure debit factor*, the difference is waste exhaust steam and should be recorded in *credit column* of Item 51.

Item 52: General Condensation

The general condensation in the boiler room and turbine room should be estimated for summer and winter conditions, and the total quantity expressed in term of *steam from and at 212 deg. fahr.*, filled in *credit column*.

Item 53: Unaccounted-For and Meter Inaccuracies

The unaccounted-for steam is the difference between Item 55 and the sum of Items 50, 51, 52, and 54 such that the *debits and credits* in Item 55 will strike a balance.

For example:

Credits, Item 50	390	*Debits*	129,200
Credits, Item 51	....		
Credits, Item 52	50		
Credits, Item 54	128,740		
Total credits	129,180	*Debits*	129,200
		Credits	129,180
		Difference	20

Hence Item 53 = 20, and should go in *credit column*.

Item 54: Net Steam Output

Fill in *credit column*, quantity given in Item 39, Column C, *net consumption;* for example, 128,740.

SECTION III FUEL CONSUMPTION

Items 56–66

The heat value of the fuel should be determined by periodic analyses and a weighted average value should be used. For example, heat value *dry*, 13,610; *as fired*, 13,490.

The column headed "Service" should be used to show the service for which coal has been banked, that is, coal in excess of that necessary for ordinary steam requirements, for electric power, testing steam or any other service. The usual charge for banking coal is one-half pound per hour banked per boiler horse-power rating. The *car weights* in 2000-lb. tons ordinarily should be used in estimating the *total million B.t.u.* values and calculating the efficiencies. The *power-house weights* should be shown as a check on the *car weights*. In the consumption of total *million B.t.u.*, use *dry heat values*. This means that the efficiencies will be somewhat lower, but due to difficulty of determining moisture in coal as fired the dry value is preferable and this will probably in long run operate with no greater weight against any one plant than any other.

SECTION IV PLANT DATA

Items 67–74

These items should be obtained from the manufacturing departments and the data are recorded to show correlations between manufacturing activities and consumption of services. They should correspond to and be representative of the period covered by this report.

SECTION V ELECTRIC POWER GENERATED

Items 75–81

The kilowatt-hours generated by each machine should be recorded in the first three columns, segregated according to how they are produced, and repeated in the last three columns segregated according to voltage. See description under Items 1 to 6 for method of calculating kw-hr. generated by extraction or mixed-pressure tubines. *High tension* refers to voltages used in main distribution, that is, above 600. *Low tension* refers to utilization voltages, that is, 110, 220, 440, 550 a.c. D.c. refers to direct-current at any voltage.

For example, Turbine No. 1, meter reading 38,000 kw-hr. This was generated condensing, and at high tension. For the *mixed-pressure* machine, total kw-hr. were 250,000 as obtained from meter readings. Now with h.p water rate of 15 lb. per kw-hr., $\frac{3,000,000}{15} = 200,000$ kw-hr. hp. condensing.

Whence low-pressure condensing 250,000 — 200,000 = 50,000 kw-hr. Whence enter in columns of Item 78.

For an *extraction turbine* the total kw-hr. were by meter, say, 234,200
High-pressure condensing flow 1,000,000 lb., and with water
rate 20 lb. per kw-hr. $\frac{1,000,000}{20} = 50,000$

Hence kw-hr. from steam extracted 184,200

These data should be entered in Item 81.

Items 82–86

Record power for these auxiliaries in appropriate columns.

Item 87

Deduct totals of Item 86 from Item 81.

Item 88

Record ratio *total net kw-hr.* to *total kw-hr. generated;* e.g., $\frac{2,056,400}{2,117,500} =$ 97.2 per cent.

SECTION VI ELECTRIC POWER CONSOLIDATED

Items 89–94

The *maximum demand* should be the highest peak generated or purchased during the month. The *total maximum demand* may not be the sum of the individual peaks but should show, if possible, the complete load peak. Whatever basis is used in determining peaks on purchased power should be applied for the generated power also. The power factor should be the average power factor during the peak loads; for example, 85 per cent.

SECTION VII NET POWER FOR DISTRIBUTION

Items 95–100

In order to show if the character of the power generated or purchased best meets the distribution requirements and to get an approximation of the losses involved in transforming it to suitable voltages or converting it from d.c. to a.c., this table should be filled in.

The losses resulting in the distribution from the power house or the conversion losses from a.c. to d.c. for utilization in factory should not be included. Show in the first four columns the total kw. dealt with; that is, transformed or converted, etc. This will be the same as that given in Item 93. In the two succeeding columns show the net power derived. The difference between the two sets of columns will show the losses, which should be deducted from Item 93, *total*.

Item 100: Unaccounted For

The unaccounted for electric power should be placed in Item 98, such that Item 124 equals Item 93.

SECTION VIII ELECTRIC POWER DISTRIBUTION

Items 101–127

The use of this record should be obvious. The maximum demand records will be kept only if convenient.

SECTION IX PLANT STATISTICS

The plant performances for the previous four (4) months should be filled in to show the relative efficiencies for the different seasons.

Item 129: Total Net Steam

This quantity is taken from Item 54, *credit column*, and divided by 1000.

Item 130: Net Steam in Per Cent of Gross Steam

This is the per cent figure, Item 54.

Item 131: Boiler-Capacity Factor

The *boiler capacity factor* is based upon the total boiler horsepower installed—not on that which is active. An abbreviated formula for this is:

$$\frac{\text{1000 lb. steam from and at 212 deg. fahr. (Item 49)}}{\text{Boiler hp. installed} \times \begin{cases} 29 & \text{for 5-week month} \\ 23.2 & \text{for 4-week month} \end{cases}} \times 100\%$$

This accordingly represents the average load as a per cent of all the boiler capacity installed whether active or not.

Item 131: Boiler Load Factor

The *boiler load factor* refers to the average load on all boilers under steam, exclusive of idle and banked boilers. Unlike load factors for electric power, it is given in terms of boiler rating as being the peak. An abbreviated formula follows:

$$\frac{\text{1000 lb. steam from and at 212 deg. fahr. (Item 49)} \div 34.5}{\text{Boiler hp-hr. in Service}} \times 100\%$$

Item 133: Thermal Efficiency Boiler Room (Including Banking)

The thermal efficiency, including banking coal, is given by the following:

$$\frac{\text{1000 lb. steam from and at 212 deg. fahr. (Item 54)} \times 0.97}{\text{Million B.t.u. (Item 66)}} \times 100\%$$

NOTE: This is the efficiency of the whole boiler room, including all losses not just the boiler efficiency. For example:

$$\frac{128{,}740 \times 0.97}{173{,}300} = 72\%$$

Hence, efficiency, Item 133, is 72%.

Item 134: Thermal Efficiency Boiler Room Excluding Banking

The thermal efficiency of boiler room excluding banking is given by:

$$\frac{\text{1000 lb. steam f. and a. 212 deg. fahr. (Item 54)} \times 0.97}{\text{Million B.t.u. (Item 62)}} \times 100\%$$

For example: $\frac{128{,}740 \times 0.97}{170{,}578} \times 100\% = 73.2\%$.

Item 135: Boiler Efficiency Including Banking

The boiler efficiency including banking is given by:

$$\frac{\text{1000 lb. steam f. and a. 212 deg. fahr. (Item 49)} \times 0.97}{\text{Total million B.t.u.}} \times 100\%$$

For example: $\frac{129{,}200 \times 0.97}{173{,}300} \times 100\% = 72.5\%$

Items 136–142

These items should be recorded from averages of meter readings. The *general condensate temperature* (Item 139), is the average temperature of all returns and make up before being heated in the feed heater, and is hence the base for all calculations.

SECTION X ELECTRIC POWER

Item 144: Thousands of Net Kw-hr. per Month

This is net kw-hr. generated, Item 87 divided by 1000.

Item 145: Generator Capacity Factor

The generator capacity factor is given by:

$$\frac{\text{Total kw-hr. generated}}{\text{Installed kw.} \times \text{hr. per month}} \times 100\%.$$

For example, with 7500 kw. total installed capacity,

$$\frac{2{,}117{,}500}{7500 \times 5 \times 24 \times 7} \times 100\% = 33.7\%$$

Item 146: Load Factor

The generated power *load factor* is given by the following:

$$\frac{\text{Total kw-hr. generated net (Item 87)}}{\text{Kw.-demand (Item 89 or 90)} \times \text{hr. per month}} \times 100\%.$$

Example:

$$\frac{2{,}056{,}400}{6500 \times 0.85 \times 5 \times 7 \times 24} \times 100\% = 44.2\%$$

Item 147: Power Factor

Record average *power factor* from meter readings.

Item 148: Thermal Efficiency Generated Power

The thermal efficiency of the generated power is given by:

$$\frac{\text{Net kw-hr. generated (Item 87)} \times 3.412 \times 100\%}{\text{Net consumption (Item 10G)} \times 970} \times \text{B. R. Eff. (Item 133)}$$

Example:

$$\frac{2{,}056{,}400 \times 3.412 \times 100}{13{,}810 \times 970} \times 0.72 = 37.6\%$$

NOTE: The greater the percentage of non-condensing power the higher will this efficiency be.

Item 149: Pounds of Coal per Kw-Hr.

The pounds of coal per kw-hr. is given by the following:

$$\frac{\text{Net steam (Item 10)} \times 2000 \times \text{total tons coal (Item 66)}}{\text{Total net steam (Item 54)} \times \text{net kw-hr. generated (Item 87)}}$$

For example:

$$\frac{13{,}810 \times 2000 \times 6376}{128{,}740 \times 2{,}056{,}400} = 0.668 \text{ pound per kw-hr.}$$

NOTE: This figure is low where non-condensing power is relatively large and is hence sometimes misleading.

Item 150: Total Power-House Interruptions

Interruptions caused by internal power-house troubles should be recorded in aggregate minutes per month.

Items 151–156: Kilowatt-Hours per 1000 Lb. Steam

The kw-hr. per 1000 lb. steam is the ratio of total kw-hr. generated by a unit to the thousands of pounds of steam from and at 212 deg. fahr. consumed by this unit as read in Column G, Items 1 to 6. These data are given to show the relative merits of different units and the loss of efficiency year by year, due to wear of buckets, poor vacuum, etc. For example:

Unit Number	Kw-Hr. Total	1000 lb. Net Steam	Kw-Hr. per 1000 Lb. Steam
1	38,000	850	44.7
2	1,633,300	5550	294
4	250,000	5350	46.7
6	234,200	1950	120

The wide variation in these ratios is due to the varying percentages of non-condensing power.

Item 157: Kw-Hr. per 1000 Lb. Steam—Station

The station kw-hr. per 1000 lb. steam are determined similarly to Items 151 to 156 except that the gross steam to power is used and net kw-hr. generated. For example, $\frac{2{,}056{,}400}{13{,}810} = 148.5$. The idea of this item is to give an overall value of performance.

SECTION XI COMPRESSED AIR

Items 158–164

Delivery should be obtained from meter readings. *Demand* should only appear in Item 164. The kw-hr. should be obtained from distribution meter readings. 1000 lb. steam from and at 212 deg. fahr. obtained from Items 23–27. The *performance* is the total cu. ft. delivered per kw-hr. or 1000 lb. steam from and at 212 deg. fahr. *Demand* is the maximum rate of delivery in cu. ft. per minute averaged over any 10-minute period. Record if metered.

SECTION XII WATER

Items 165–171

These data should be obtained from meter readings. Cross out "gallons" or "cubic feet," whichever is not the correct unit. *Demand* is here the maximum hourly rate of supply averaged over 10 minutes. Record if metered.

Item 172: Total

Sum up items under *Consumption*. In *Demand* column should be placed maximum demand for water during month, expressing as a rate per hour—taking the 10-minute peak and multiplying by 6.

Item 173

Only figure in total demand column. This is to be maximum simultaneous hourly rate of consumption for a period of 10 minutes taken by considering the maximum simultaneous drafts for all services. Record if data available.

Joint Research Committee on Boiler-Feedwater Studies

FIVE national technical organizations are coöperating actively in a study of the various processes employed in the purification of feedwater in steam power plants and on railroads. This research is being carried on to determine the fundamental principles underlying certain phenomena which take place in steam boilers. The Joint Research Committee on Boiler-Feedwater Studies sponsored by the American Railway Engineering Association, the American Water Works Association, the National Electric Light Association, the American Society for Testing Materials, and The American Society of Mechanical Engineers, has been subdivided into nine Sub-Committees and an Advisory Committee. Each Sub-Committee is collecting data relating to the subject assigned to it, and has been requested to compile and submit yearly reports. After these reports are reviewed by the Advisory Committee they are presented for publication in the journals of the technical organizations participating in these studies. Nine of these reports appear below.

A number of papers originated by this Committee were read at the meeting of the American Water Works Association in Buffalo, N. Y., in June, 1926. Some of these papers are reproduced in the October, 1926, issue of MECHANICAL ENGINEERING.

Pretreatment of Boiler Feedwater

Progress Report of Sub-Committee No. 2 on Water Softening by Chemicals (External Treatment)*

BY CLARENCE R. KNOWLES, CHICAGO, ILL., CHAIRMAN

THE following subjects were assigned to Sub-Committee No. 2 for investigation and report:

1 The chemical reactions to be considered in the light of present knowledge of physical chemistry, with special attention to the hydrogen-ion concentration of water and its influence upon the precipitation of hardening salts.

2 Compilation of operating data to determine the relative value of continuous and intermittent softeners.

3 Collection of operating figures showing the efficiency of subsidence tanks and basins in order to be able to submit recommendations for the more efficient design of basins for precipitation of solids and the removal of sludge.

4 The causes and prevention of retarded chemical reaction.

5 Standardization of rates of filtration employed for the removal of suspended solids from softened water.

6 The effect of siliceous material as a filtering material when used in conjunction with hot chemical softeners, and the value of non-siliceous filtering material.

7 A consideration of the economic value of lime-soda softener treatment preliminary to zeolite softeners or to evaporators.

8 Standardization of nomenclature employed in the field of softening of water by chemicals and of the apparatus and appurtenances in use in these systems.

Your Committee presents reports on the above subjects as follows:

Study A—Report on the relative value of continuous and intermittent water softeners.

Study B—Report on the economic value of lime-soda softening preliminary to zeolite softening.

Study C—Report on the economic value of lime-soda softening preliminary to evaporators.

Study A—Operation of Continuous and Intermittent Lime-Soda Water-Softening Plants

THE investigation of this subject has necessarily been broadened somewhat to include a study of the typical equipment employed in each type of softening plant, in view of the intimate relation existing between the installation and operation in both cases. As any manufacturer of water-purification equipment may build either the continuous or intermittent type of apparatus, subject only to the limitations of his technical knowledge and engineering skill, it was felt that an impartial study of this important angle of the problem could be made.

A typical continuous softener, as its name implies, provides for the continuous treatment, settling, and filtration of a water at either a constant or variable rate of flow through the apparatus. Ordinarily the retention period provided is four hours, with the softener running at its full rated capacity, although in some cases this has been decreased slightly and in others has been materially increased.

The typical intermittent softening plant comprises two or more tanks which are filled, treated, and emptied by the batch method, together of course with the necessary auxiliary equipment. In this case, also, the minimum time for which each tank is in service is 4 hours; but in this case a half-hour is provided for filling the tank, a minimum of $2^1/_2$ hours for settling, and 1 hour for emptying. The service period of each tank and the number of tanks is frequently increased.

COMPARISON OF EQUIPMENT

Size of Reaction and Settling Tank. The typical intermittent plant requires a total tankage of at least 50 per cent more than the continuous plant, and usually requires at least twice as much floor space.

Storage. Since a tank of the intermittent plant must be emptied rapidly, in order not to waste the settling capacity of the tank, provision is generally made to accomplish this emptying in not more than an hour. The treated water is discharged through filters into a clear-well with a capacity usually equal to $1^1/_2$ to 2 hours normal water consumption, or more.

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* The personnel of Sub-Committee No. 2, on Water Softening by Chemicals (External Treatment), of the Joint Research Committee on Boiler-Feedwater Studies is as follows:

CLARENCE R. KNOWLES, *Chairman*, Superintendent of Water Service, Illinois Central Railroad, 135 East 11th Place, Chicago, Ill.

A. M. BUSWELL, Dr., Director, Water Survey, Urbana, Ill.

A. S. BEHRMAN, International Filter Company, 333 West 25th Place, Chicago, Ill.

C. W. DEFOREST, Manager, Electric Department, Union Electric Company, 4th and Plum Streets, Cincinnati, Ohio.

HAROLD FARMER, Chief Chemist, Philadelphia Electric Company, Philadelphia, Pa.

C. P. HOOVER, Chemist and Superintendent, Water and Sewage Department, Columbus Filter Plant, Columbus, Ohio.

C. P. VAN GUNDY, Superintendent, Water Service, Baltimore and Ohio Railroad, Baltimore, Md.

JOSEPH D. YODER, Charge of Water Purification Department, H. S. B. W.-Cochrane Corporation, 3107 North 17th Street, Philadelphia, Pa.

Progress reports read and discussed at a joint session of the A.S.M.E. Power Division and the Joint Research Committee on Boiler-Feedwater Studies at the Annual Meeting, Dec. 6 to 9, 1926 in New York.

Be sure to bring this copy with you to the Annual Meeting

Obviously the continuous softening plant does not require storage of this sort, since it is delivering treated and filtered water uninterruptedly and can meet the demand as it occurs.

Filters. Assuming that an intermittent tank holds a 4-hour supply of water and is emptied in 1 hour, it is obvious that considerably greater filter capacity must be provided than for the continuous softener in which the same total quantity of water is distributed over a 4-hour period.

Pumps. If pumping of the raw-water supply to the softener is necessary, the intermittent plant will require pumps with about four times the capacity of those needed for the continuous plant, since the volume of water pumped into one of the intermittent tanks in an hour is distributed in the case of the continuous plant over a 4-hour period. Much of this head is lost in the case of the intermittent plant due to the decreasing head as the tank is drained. In the continuous plant, with a draw-off of the treated water at the top of the tank, the head is retained in large measure.

Mixing Chemicals with Water Being Softened. In the continuous type of apparatus, where a relatively small amount of water is being treated at any given moment, it is not particularly difficult to secure good mixing of the chemicals with the waters being softened. In the intermittent system, in which the entire tank supply is treated at once, special provision must be made for the distribution of the chemical reagents throughout the large mass of water being treated. In small plants mechanical stirrers may be employed. In larger plants, compressed air is usually the agent employed for agitation, a compressor and auxiliaries thus becoming an essential unit in this type of plant.

Initial Cost. The initial cost of an intermittent plant, installed, of reasonably large size, to meet the requirements of boiler-feed-water purification, will average from about 30 to 50 per cent more than for a continuous plant of the same hourly capacity. The difference in the overhead expense of the two plants thus becomes an item of importance in considering the operation of the apparatus.

Comparison of Operation

Cost of Chemicals. The amount of chemicals required in either case is approximately the same. It is standard practice in the case of the intermittent plant to employ a coagulant, usually sulphate of iron, in addition to the lime and soda required for treatment. The use of a coagulant is not standard practice with all continuous plants, but the evidence in many cases indicates that the improvement in results of the water treatment in such cases effected by the use of a coagulant is sufficient justification for the additional expense.

Cost of Power for Operation. The total cost of the power necessary for operating these plants is not vastly different for the two types, except in special cases in which the larger pumping cost for the intermittent plant may amount to a considerable item of expense.

Cost of Labor. In very large plants, say, 50,000 gal. per hour or more, the amount of labor required for the two types of plants is approximately the same, since in both cases the entire time of one man is usually devoted to the care and operation of the plant. In smaller plants, however, there is a marked difference in the amount of labor required. For plants ranging from those of very small size up to about 20,000 gal. per hour, the total time required in the case of the continuous softener should not exceed about 3 hours; while in the case of the intermittent plant, practically the entire time of one man will be required.

This difference in the amount of labor involved is due, of course, to the fact that in the case of the continuous softener the chemical feeding tanks may be filled very quickly with enough of the reagents to treat water for a good many hours' supply; or in the case of the intermittent softener the succession of filling, treating, and emptying operation is necessarily so frequent that a man's time is pretty well occupied.

Comparison of Results Obtained

Assuming proper operation in both cases, properly treated water can be obtained from either type of apparatus. The particular field of usefulness of the intermittent type of softener has been held to be for waters of variable composition, such as those of rivers and of other sources of supply. The validity of this statement is not evident upon a careful examination of the method of operation of a typical intermittent softener, nor of the results obtained. The ideal way to handle water in an intermittent softener, of course, is to take a sample of the water shortly after it has been thoroughly mixed with chemicals, and from tests on this water determine what change, if any, is necessary in the treatment. If a change is found necessary, which could easily be the case with a water of changing composition, the tank of water would have to be held until the treatment was adjusted either by the addition and agitation of more chemicals, or by the waste of treated water to allow for dilution with enough raw water to compensate for the overtreatment. The loss of time involved here would so lessen the effective period of service of a tank that the number of tanks would have to be increased to provide for such contingencies. Observation of the actual operation of intermittent plants shows that as a rule the charge of one tank is based upon the chemical test made on the water of the previously treated tank; that is, the treatment of any particular tank is at least one tank behind any change in composition of the water.

In general, the human element would seem to play a greater part in the operation of an intermittent softener than in a continuous plant, since the number of man-made operations is considerably greater during the course of a day's operation.

Study B—Economic Value of Lime-Soda Softening Preliminary to Zeolite Softeners

THE economic value of lime-soda softening preliminary to zeolite softening is dependent upon so many conditions that perhaps the best that any committee can do for the guidance of the general public in this respect is to point out the conditions which will affect the economic value of preliminary treatment so that these points will be given consideration when this question is decided.

Such preliminary treatment as the water requires for filtration purposes may be disregarded, for it is assumed that it is well understood that all waters containing suspended matter must be satisfactorily filtered before delivery to a zeolite softener. Whether or not sedimentation must be provided ahead of the filters is purely a filtration problem. The water must be made crystal clear before delivery to a zeolite softener.

Consideration must be given to the following:

1 *Direct Use to Which Softened Water Will Be Applied.* If the softened water is to be delivered to evaporators the presence of a large amount of sodium carbonate will not necessarily be seriously objectionable. Likewise, the sodium carbonate is not objectionable if required to soften the make-up water of the circulating system when using a cooling pond, to prevent scale formation on the tubes of surface condensers.

Where zeolite-softened water is fed directly to the boilers the high sodium carbonate resulting from this treatment is objectionable for the following reasons:

(*a*) There is a tendency to cause foaming and priming of boilers because of high alkalinity concentrations in the boiler. To prevent priming the boilers must be blown down sufficiently, the amount of water depending upon the type of boilers, the rate at which boilers are fired, and other operating conditions.

The question in this respect that must be considered is "How much less will the boilers need to be blown down to prevent priming if the water is given preliminary softening before zeolite softening than if the zeolite softener is used alone?" Clearly the blow-down losses for boilers operated at high ratings will exceed the losses for comparatively small boiler plants where customarily boilers are not much overloaded. For small boiler plants unquestionably zeolite softeners have been used with satisfaction without pretreatment, whereas for larger plants with boilers operated at considerable overload pretreatment would be necessary before zeolite softening.

(*b*) The probable effect of the sodium carbonate on caustic embrittlement of boiler plate is not well understood. The May, 1925, issue of MECHANICAL ENGINEERING gave the suggested rules for care of power boilers which contained the recommendation that for working pressures of 150 lb. and under the alkalinity in terms of sodium carbonate should not exceed the sodium sulphate; for working pressures over 150 lb. and under 250 lb. alkalinity not to exceed one-half the sodium sulphate; for working pressures of 250 lb. and higher, alkalinity not to exceed one-third the sodium sulphate.

Many waters treated by zeolite softeners will give a ratio of

sodium carbonate to sodium sulphate unfavorable to the above recommendations of the A.S.M.E. Boiler Code Committee. To determine the economic value of pretreatment from the standpoint of embrittlement it is not only sufficient to give consideration to the amount of temporary hardness in the raw water, but the amount of sulphates present must also receive consideration. This will, furthermore, obviously be dependent upon the boiler pressure. The higher the boiler pressure the more necessary the pretreatment for a given water supply.

The after-treatment of a zeolite-softened water with sulphuric and phosphoric acid is now being done in a number of commercial plants to lower its alkalinity.

2 *Cost of Pretreatment.* The cost for additional equipment for pretreatment is considerably greater per thousand gallons water treated for small capacities than large. Consequently it would follow that pretreatment might prove economical for comparatively large installations, whereas it might not be economical for small capacities. The comparative costs must therefore be considered.

Again, it is obvious that the additional cost of equipment for pretreatment to lower the carbonate hardness will be considerably less if in any event the water requires filtration. Particularly is this true if the water requires sedimentation ahead of the filters. If before delivering water to the zeolite softener the water must be filtered and also settled, the additional cost for pretreatment of the water for lowering the hardness will be much less than if a city supply of well water, that does not require filtration, were available.

The cost of chemicals for removal of the temporary hardness is ordinarily less than the cost of salt, considering that for calcium carbonate hardness more than 4 lb. of salt must be used for the equivalent accomplished by 1 lb. of hydrated lime, for precipitation of magnesium carbonate 2 lb. of salt are required for the equivalent of 1 lb. of hydrated lime. The costs of salt and lime vary quite considerably, depending upon the proximity to the source of salt and hydrated lime. Freight rates have an important bearing on these costs.

Comparative cost of pretreatment must also be considered with an after-treatment of a zeolite-softened water with sulphuric and phosphoric acid which is now being done in a number of commercial plants to lower the alkalinity of zeolite-softened water.

This question must also be considered in comparison with the cost of equipment for softening the water without introducing large amounts of sodium carbonate as may be obtained by hot-process and cold-process lime and soda softeners.

From a study of the above it is evident that the question of whether or not pretreatment is advisable becomes complicated if an attempt is made to derive a formula applicable to all conditions, whereas a consideration of all the above factors generally becomes very simple for any plant if all the conditions are known. It is therefore believed that the best that this Committee can do is to point out the influencing factors, the most important of which have been mentioned above.

Study C—Economic Value of Lime-Soda Softening Preliminary to Evaporators

THE economic value of lime-soda softening preliminary to evaporators is dependent upon so many conditions that a number of the recommendations made for pretreatment to zeolite softeners in our previous report will be applicable to pretreatment for evaporators.

A survey of the central stations using evaporators indicates that waters containing 10 grains or more "total hardness" are being given pretreatment, and that waters containing 6 and 7 grains total hardness are being evaporated without apparently giving serious trouble.

A total of 55 questionnaires were sent out to central stations throughout the country, using evaporators, requesting data relative to operating conditions, cleaning, nature of water, etc. The results of this survey are classified as follows:

Class 1—18 questionnaires have not been acknowledged. (32.7 per cent.) A second attempt was made to obtain data from these companies but apparently without success. The possible explanation for this may be that questionnaires were addressed to holding companies as well as to the individual company.

Class 2—13 users acknowledged the questionnaire, but for various reasons have not furnished information. (23.6 per cent.) These were returned not filled out for various reasons: equipment not yet in service; equipment in stand-by plants; equipment not been in service long enough to accumulate data; no available data, etc.

Class 3—24 users returned the questionnaire filled out as requested. (43.7 per cent.) These questionnaires returned containing the requested data have been carefully analyzed, and from this information our report has been prepared.

The analysis of the questionnaires indicates that 42 per cent of the users regard pretreatment warranted on account of scale, but 58 per cent of the users regard pretreatment not warranted. Of the 42 per cent who regard pretreatment warranted, 21 per cent use external softeners, 12.6 per cent use internal treatment, but do not regard it satisfactory, and 8.4 per cent give no treatment but recommend it.

A careful examination of the chemical analysis of the waters used by the above installations indicates that with the exception of one water all have a "total hardness" of 10 grains or higher. The one exception has a "total hardness" of only 6 grains. Of the 58 per cent who regard pretreatment *not* warranted, 53.9 per cent use water less than 6 grains "total hardness," and 4.1 per cent use water of 7 grains "total hardness."

One installation of the above 58 per cent treats the water with sulphuric acid to give a more favorable relation of sodium sulphate to sodium carbonate on account of water naturally containing 6 grains of sodium carbonate per gallon. This is done because evaporator gives off some moisture, and soluble salts are formed in the distillate.

It would be a difficult matter to try to indicate the average saving in dollars and cents to be obtained by pretreatment ahead of evaporators as there are so many variables to be considered, i.e., the amount of water evaporated between cleanings; the condition of the water; irregular cleaning periods ranging from one week to one year; reduction in capacity varying from 2 to 50 per cent, and cost of cleaning varying from $20 to $600.

The cost of additional equipment for pretreatment might be considerably greater per thousand gallons of water treated for small capacities than for large capacities; consequently it would follow that pretreatment would prove economical for comparatively large installations, whereas it would not be economical for small capacities.

The most significant facts brought out by this investigation are that waters containing 10 grains or more "total hardness" are being given pretreatment, and that waters containing 6 and 7 grains "total hardness" are being evaporated without apparently giving serious trouble.

In conclusion, we wish to thank the central stations for the generous manner in which they furnished us with the information requested.

Present Knowledge of Foaming and Priming of Boiler Water, with Suggestions for Research

Progress Report of Sub-Committee No. 3 on Zeolite Softeners, Internal Treatment, Priming and Foaming, and Electrolytic Scale Prevention*

By C. W. FOULK, COLUMBUS, O., CHAIRMAN

IN 1863 Stromeyer[1] in his work on marine boilers wrote that information on the subject of priming was "almost non-existent." Eighteen years later Stabler[2] evidently felt that little information had been added, for he began his section on foaming and priming with the statement that they "are probably the least understood of boiler phenomena." At the present day, sixteen years later, Stabler's statement still holds. The only modification that suggests itself would be to leave out the word "probably."

Phenomena to Which the Names "Foaming" and "Priming" Have Been Applied

Much effort has been expended in the past in trying to define "priming" and "foaming." A search of the literature shows utter confusion in the use of these terms. Some authors employ them interchangeably. Some call a foam on the surface "priming," and others call violent ebullition "foaming." Indeed, it can be said that a reader of any book or paper will not know what is meant unless the writer defines his terms.

Fortunately the question can be approached another way. Instead of seeking the meaning of the terms one can differentiate and describe the phenomena to which these various names have been applied. From this standpoint, then, an examination of boiler-water papers shows that one or more of three fairly distinct mental pictures of phenomena inside the boiler were in the minds of writers when they used the terms "foaming" and "priming:"

1 The formation of foam on the surface of the water. This foam may range in thickness from a layer barely covering the surface to a mass that fills the steam space above the water. In the latter case the liquid films around the bubbles would be drawn into the steam pipe and wet steam would result.

2 Another phenomenon evidently in the minds of certain writers is merely rapid ebullition with the consequent projection of droplets or even slugs of water into the steam pipe. This could happen without the appearance of foam as it is described above.

3 A third situation partakes both of the properties and appearance of foam and of violent ebullition. The boiling is of such a character that the whole mass of water from the bottom up is full of fine steam bubbles, with the consequence that the interior of the boiler is filled and of course much water passes out with the steam.

It should be emphasized, perhaps, that the three situations pictured above are not necessarily descriptions based upon actual observations of steam boilers in operation. If such observations have been made the author has failed to find the record of them. They are to be looked upon more as reasonable suppositions by men of experience with steam boilers, and who have undoubtedly observed analogous situations in glass flasks or open metal vessels. Moreover, some writers evidently have no picture in mind of what goes on inside the boiler. They simply use the terms as meaning any entrainment of water by the steam.

Systematic research may show that a fourth phenomenon, namely, the manner in which bubbles break on the surface of the water in the boiler, should also be considered, at least as one of the causes of wet steam. This idea was first suggested to the author by Dr. R. E. Hall, who used the phrase "smoothness of boiling."

It is well known that a bubble breaking on the surface of a liquid projects a droplet of the liquid to a height of several inches. This phenomenon has never been studied so that nothing is known of its mechanism or of any way of controlling it. It seems reasonable to suppose that a continual projection of droplets of water into the steam space would be a large factor—perhaps the determining factor—in causing wet steam when other conditions were normal, that is, when there was no foaming or priming.

The confusion of terms that exists is deplorable, and now that an official committee[3] representing a number of interested engineering societies is at work on this feature of boiler-water behavior, one of its first duties should be the clarification of the nomenclature. However, before permanent definitions are formulated there should be an extensive series of accurate observations made, if possible, on actual steam boilers, and failing that, on experimental boilers, in order to determine with some precision the various causes for the entry of water from the boiler into the steam. Appropriate names can then be found for the phenomena.

Causes of Foaming and Priming

Physical. The causes of foaming and priming as given in boiler-water papers fall under two general heads, physical and chemical. Among the physical causes the design and operation of the boiler are outstanding. The more complex the interior—that is, the more of a maze of tubes, staybolts, etc., there is in the boiler—the more likely is it to foam (prime). It is also evident that, other conditions being the same, the smaller the steam space above the water, the more likely is water to be carried out. If the boiler is moved about rapidly while in use, as is the case with railroad and marine boilers, the extra agitation will promote foaming.

Violent ebullition for a few seconds may result from the sudden evolution of steam following a period of superheating of the water analogous to the familiar "bumping" of liquids in the laboratory. A similar effect would be produced by the loosening of a sheet of scale, which would thus bring water into contact with almost red-hot metal. The sudden introduction of solid matter, entering with the feedwater or produced by the loosening of scale, also causes a violent ebullition for a few seconds, and a rapid opening of the steam valve by causing a momentary lowering of the pressure has the same effect.

There is some difference of opinion as to the relation of steam pressure to foaming, but the majority seem to hold that high-pressure boilers foam less than low-pressure ones. Such a statement seems logical because a given weight of steam occupies less space the higher the pressure it is under.

Chemical. The available information about the chemical causes of foaming may be classified under (1) substances that cause foaming, and (2) physico-chemical explanations of the phenomenon. The offending substances are listed under such indefinite terms as "organic matter," "impurities," "oily matter," "soap and soapy substances," "saline matter," "alkalis," and "suspended solids." Sodium salts seem to be the only definite chemical substances to which foaming and priming are generally attributed, but the author has not been able to find a record of any experiments which show that sodium salts alone are the cause of the trouble. The belief has unquestionably originated from the fact that in the great ma-

* The personnel of Sub-Committee No. 3 on Zeolite Softeners, Internal Treatment, Priming and Foaming, and Electrolytic Scale Prevention, of the Joint Research Committee on Boiler-Feedwater Studies is as follows:
C. W. Foulk, *Chairman*, Prof., Analytical Chemistry, The Ohio State University, Columbus, O.
Samuel B. Applebaum, Assistant Technical Manager, The Permutit Company, 440 Fourth Avenue, New York, N. Y.
Edward Bartow, Dr., State University of Iowa, Iowa City, Ia.
A. S. Behrman, International Filter Company, 333 West 25th Place, Chicago, Ill.
A. M. Buswell, Dr., Director, Water Survey, Urbana, Ill.
R. E. Coughlan, Chicago and Northwestern Railroad, Chicago, Ill.
D. K. French, Dearborn Chemical Company, 310 South Michigan Avenue, Chicago, Ill.
Vincent M. Frost, Assistant to General Superintendent of Generation, Public Service Gas and Electric Company, 80 Park Place, Newark, N. J.
C. P. Van Gundy, Superintendent, Water Service, Baltimore and Ohio Railroad, Baltimore, Md.

[1] C. E. Stromeyer, Marine Boilers, p. 42 (1893).

[2] Herman Stabler, *Eng. News*, vol. 60 (1908), p. 355 and U. S. Geological Survey, Water Supply Paper 274, p. 171 (1911).

[3] *Jl. Am. Water Works Assn.*, vol. 13 (1925), p. 336.

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jority of waters sodium salts are the only ones that concentrate in the boiler. Others that are present in any quantity, such as calcium and magnesium compounds, precipitate for the most part.

Next to sodium salts finely divided solid matter is held responsible for foaming and priming, and some go so far as to assert that solids are the only cause, barring, of course, occasional cases of soap or peculiar forms of organic matter in the water. Here again, however, the record of experimental evidence in favor of this view is lacking.

In 1924 the author[4] acting on a hint from Bancroft[5] succeeded in harmonizing the conflicting statements concerning the effect of sodium salts and solid matter. An extensive series of laboratory experiments showed that sodium salts alone or finely divided solids alone did not cause a true foam, but that when both were in the water in sufficient concentration foaming resulted; that is, a true foam or froth several inches thick was produced on the surface of the water. The explanation of this is given below.

THE PHYSICO-CHEMICAL THEORY OF FOAMING

Wherever the word "foam" or one of its derivatives is used in this section, it refers to a true froth or foam as described in No. 1 above.

It must be said at the start that there is as yet no comprehensive physico-chemical theory of foams. This fact, perhaps more than any other, retards the progress of research in this field. The statement frequently found that foaming is caused by lowering the surface tension of a liquid seems merely to express a coincidence. While it is true that the foamiest liquids (for example, soap and saponin solutions) have low surface tensions, it is also true that pronounced foaming can be produced by conditions that raise the surface tension. Water solutions of inorganic substances—sodium salts, for example—foam readily if the films are stabilized by finely divided solid matter. (See below.)

Furthermore there is no quantitative relation between the lowering or raising of the surface tension of a liquid and the foam producing power of the resulting solution. Water solutions of soap and saponin, for instance, may be equally foamy, the saponin even foamier than the soap, and yet the surface tension of the saponin solution will be much higher than that of the soap.

This question of the lack of relation between surface tension and foaming is discussed at length by W. Ostwald and A. Steiner,[6] who give many literature citations. The immediate relation of the problem to boiler water is touched upon by Millard and Mattson,[7] who show that what they call "priming" is in no way related to surface tension. Though these investigators do not distinguish between true foam and other phenomena, the description of some of their experiments leads one to think that foam should have been present.

About all that can be said is that pure liquids do not foam.[8] Something must be present of such a nature that its concentration in the surface differs from that in the mass of the liquid. This interesting situation is quite common and can be shown by laboratory experiments. If, for example, a mass of soap bubbles is collapsed the resulting liquid will be found to contain more soap per unit volume than did the original solution from which the bubbles were produced. Whether there is more or less of the added substance in the surface than in the interior of the liquid seems to make no difference. Either way, the surface layer differs from the rest of the liquid and thus makes possible a separation of films from the surface. This separation of films is the necessary condition for the formation of foams. There is, however, another condition which, if not theoretically necessary is practically so, namely, the stabilization of the films. Most bubbles burst in the moment of their formation and therefore cannot form a foam. The films of a true foam must have a certain structural strength and period of existence. This is given by the viscosity of the film itself, as in the case of soap bubbles, or by the addition of finely divided solid matter which imparts the necessary viscosity, as in the case of the foams of sodium salt solutions stabilized by pulverized boiler scale. (See below.)

No one has yet offered a plausible explanation of why a pure liquid does not foam and why a difference in concentration between surface and interior of a solution permits the separation of films. When a bubble generated in the interior of certain solutions rises to the surface it lifts a film; or when a ring composed of any solid that is wet by the liquid is applied with appropriate technique to the surface and lifted, a film is removed. What now determines the plane of separation of that film from the remainder of the liquid? The answer to that question would be the general theory of foaming.

The author believes that research on this fundamental problem should be directed to a study of the conditions which control the maximum *thickness* of films. Heretofore attention has been focused on their minimum *thinness*. Bancroft,[9] who is an omnivorous reader, says, "I have not been able to find any statement as to the maximum thickness of a soap-bubble film; but it is certainly not less than 1.4μ." This is many hundred times as thick as the layers of oriented molecules pictured to account for surface-tension phenomena. In general, it would be well to direct research to the relatively thick (1.0 ± mm.) layer at the surface of liquids. It is the seat of peculiar phenomena. Liebreich called it the "dead space in chemical reactions" because certain reactions at least fail to take place in it. Hannan[10] refers to another phenomenon peculiar to this region, namely, the very rapid rate of sedimentation in it.

The relation of surface concentration to surface tension is in the sense that those substances which concentrate in the surface lower the surface tension, and those which recede from the surface increase the surface tension. It can also be shown both theoretically and practically that surface tension can be lowered to a much greater extent than it can be raised.

In general, organic substances lower the surface tension and inorganic ones raise it. There are, however, exceptions to this rule. Cane sugar, for example, slightly increases the surface tension of water and hydrochloric acid slightly lowers it.

APPLICATION OF THEORY TO BOILER WATER

On applying these principles to boiler water, it can be said that the fundamental condition of foaming is the presence of substances which concentrate either in the surface or in the mass of the water. If, however, these substances do not at the same time have the property of making the films around the bubbles stable, there will be no foam in a practical sense, because the life of the bubbles will be too short—they will burst a moment after forming. It is necessary, then, to distinguish carefully between the two conditions for the formation of foam—(1) the presence of something which, by modifying the surface of the water, makes possible the formation of bubbles, and (2) the presence of something which by imparting viscosity to the films will stabilize them—that is, prevent them from bursting immediately after forming. This necessary viscosity can, of course, be produced by the same substance which changes the surface. Soap, for example, is such a substance, and an occasional water is found in which the organic matter present has this property, either as it enters the boiler or after modification by the action of the superheated water. In the average boiler water, however, the change in the surface is brought about by dissolved sodium salts and the stabilization of the foam by finely divided solid matter. The presence of either one without the other is not sufficient to cause foaming.

The action of the particles of solid in stabilizing the foam appears to be purely mechanical. Edser,[11] in a paper on ore flotation, pictures the situation as follows:

> Imagine a number of bubbles in the interior of a liquid, each bubble being coated with mineral particles. When these coated bubbles come into contact after rising through the liquid, the walls of each cell will consist of numerous solid particles held together by films of liquid.

In flotation the solid particles are frequently the only stabilizing agent present. It must, of course, be emphasized that to stabilize a boiler-water foam as well as that of a flotation process the solids must have the property of adhering to (being adsorbed on) the

[4] C. W. Foulk, *Ind. & Eng. Chem.*, vol. 16 (1924), p. 1121.

[5] Applied Colloid Chemistry, General Theory, p. 268. McGraw-Hill Book Co., N. Y. (1921).

[6] *Kolloid-Zeitschrift*, vol. 36 (1925), p. 342.

[7] E. B. Millard and T. E. Mattson, *Ind. & Eng. Chem.*, vol. 17 (1925), p. 685.

[8] Freundlich, Kappillarchemie, 2nd. Ed., p. 1091 (1922).

[9] Applied Colloid Chemistry. General Theory, Second Edition, p. 456. McGraw-Hill Book Co., N. Y. (1926).

[10] Frank Hannan, *Jl. Am. Water Works Assn.*, vol. 10 (1923), p. 1035.

[11] Edwin Edser. Fourth Report on Colloid Chemistry, and Its General and Industrial Applications, British Association for the Advancement of Science, p. 263.

films. Flotation as a method of separation would be impossible if solids did not behave differently in this respect and, it might be added, boiler foaming would be a rare occurrence were it not for the unfortunate circumstance that the solids usually present in a boiler have the property of adhering to the films around the steam bubbles.

Whether there is a manifest difference in the stabilizing effects of the different types of boiler scale has not yet been determined. Work now in progress in the author's laboratory suggests at least that this point should be investigated.

Other things being equal, the stabilizing effect increases as the size of the solid particles decreases. It is interesting, however, to note that particles so large that none will pass through a forty-mesh sieve can be seen adhering to the steam bubbles.

Koyl[12] gives the presence of finely divided solids as the cause of the phenomenon described above under (3), but merely states that each particle becomes a nucleus from which a stream of steam bubbles rises. It would not be too far-fetched to assume that the particles that act in this way have entrained minute bubbles of air, or perhaps of carbon dioxide, which would then serve as permanent gas-phase surfaces at which steam bubbles would form. The stabilizing effect of the finely divided solid matter would tend to hold such steam bubbles intact—that is, prevent them from coalescing. In this way the mass of the water would become filled with bubbles, as Koyl describes.

In the author's previously mentioned paper a large number of laboratory experiments in glass flasks are described. This experimental evidence is too long to reproduce here, but is referred to because it furnished the confirmation of the theories advanced and which are given above. There is also another reason for referring to it. Ordinarily, laboratory experiments offer an unsafe guide for large-scale industrial operations, so that it is worth while in this case to record that the author has received additional evidence in the shape of a number of letters from persons of practical experience with steam boilers. These letters uniformly uphold the general conclusions of the paper, so that, in a way at least, it can be said that these laboratory experiments have been confirmed in practice.

Organic Matter as a Cause of Foaming

Practically nothing is recorded concerning causes of foaming other than those mentioned above. The author has received two private communications to the effect that excelsior used as a filter in a water softener caused foaming during the first few days it was in use, after which the effect disappeared. This would mean of course that the water dissolved out certain organic materials that caused the trouble. Another communication cited the organic matter in certain of the highly colored surface waters of Florida as a cause of foaming. It would be interesting to know whether such colored waters from other parts of the country have the same effect, for example, those from New England. The question of the behavior of these waters, if at the same time they contain sodium salts and finely divided solids, is one that has not yet been studied.

Testing Water to Determine Whether It Will Foam

A practical question naturally arises, namely, what chemical or physical tests can be made on a boiler water in order to determine whether it will foam? This point has never been thoroughly studied. Boiler-water chemists would determine the sodium-salt concentration and base their conclusions on the result. Stabler (Footnote 2) in his famous paper giving equations by which the behavior of a water can be calculated, includes one on foaming which gives what he calls the "foaming coefficient." It is nothing more than an approximate value for the sodium and potassium salts in the water, and obviously would not apply unless finely divided solids were also present. If sodium salts and suspended solids were both measured a very good guess could be made as to the foaming susceptibility of the water. Unfortunately, however, it would not be safe to reason in the converse way, because some waters that are very low in sodium salts and suspended solids nevertheless will foam.

A foam test is still to be devised. Some preliminary work in the author's laboratory suggests the possibility of developing something practical from so simple an operation as blowing air into the water to be tested. If the air enters in very fine bubbles, as when blown through a porous septum, a foam seems to be produced, even at room temperature, in all waters that foam on boiling, and vice versa. There is also the "membrane meter" of W. Ostwald and Steiner (Footnote 6). These investigators found that when the level of a liquid in a capillary tube is raised or lowered the rate at which the liquid surface returns to its original position is inversely proportional to the foaming susceptibility of the liquid. The original paper must be consulted for the details of the experiment.

In applying these or any other test to a boiler, however, one must not forget that the raw water and the same water after it has been subjected to the high temperature of the interior of a modern steam boiler are by no means the same things. Nevertheless the development of a foam test is worth some research.

Priming

"Priming" as used in this section has a special meaning, namely, the projection of water into the steam space due merely to violent ebullition. In most cases, perhaps, it results from the ebullition of spasmodic violence accompanying the breakdown of a condition of superheating. Unpublished work done in the author's laboratory shows that in glass flasks at least it is far easier than has been supposed to heat water above its normal boiling point for the pressure of the moment. Indeed, the water may be boiling, that is, copious bubbles of steam may be rising through it, and yet its temperature will be one or two degrees fahrenheit above the normal boiling point. If now, with the water in this condition, it is subjected to a shock of some sort, like the introduction of a little solid matter or the addition of a slug of water from the outside, the superheated state breaks down and the stored-up energy is dissipated by a few moments of violent ebullition, the temperature of course falling to the normal. Every one of course knows these facts about the superheating of liquids, but it is doubtful if many know how common the phenomenon is.

Other experiments were of the following nature. Flasks were so equipped that the steam from the boiling water in them escaped through a small orifice and therefore some inside pressure could be maintained and at the same time have the boiling proceed. If now a large valve in the stopper were opened the pressure of course dropped, the water was left at a temperature a degree or so above its normal boiling point for the lower pressure and consequently there was violent ebullition for a few seconds, so violent that large slugs of water were projected into the steam space.

If a similar situation can occur in a boiler when the steam valve is rapidly opened, the violent ebullition that will follow for a few seconds may easily throw slugs of water into the steam line. The important point to note in these experiments is that this "priming" as it is called, can take place with pure water. It is independent of the conditions of film formation, etc., that are necessary for "foaming," in other words it is a separate phenomenon and therefore merits study as such.

The question naturally arises, what happens when the flasks are charged with sodium-salt solutions alone, suspended solids alone, or with both sodium salts and suspended solid matter? The answer is, that dissolved matter alone or suspended matter alone increases the "priming" only slightly but when both dissolved and suspended matter are present the priming is many fold that of pure water. The effect described in No. 3 above can be observed at times, that is, the water lifts by becoming a mass of steam bubbles. Owing to the fact that "priming" is so greatly increased in a water in which the conditions for the formation of stabilized films also exist, it is difficult to distinguish between "priming" and "foaming." In the situation just described it would be logical to say that the "foaming" was greatly increased during a few seconds by the "priming."

The Projection of Droplets of Liquid by Bursting Bubbles

So far as the author is aware, no studies have ever been made of the nature of evaporation from the standpoint of the projection of droplets of liquid into the steam space by the bursting of bubbles. Perhaps very slight additions of the right substances to a boiler water would cause its boiling to proceed with such "smoothness" that little or no water would be thrown up. The idea is fanciful, but nevertheless is worth at least a little laboratory experimentation.

[12] *Railroad Gazette*, vol. 32 (1900), p. 663.

REMEDIES FOR FOAMING AND PRIMING

The two outstanding methods of reducing foaming and priming are (1) reduction of the concentration of sodium salts, suspended solids, or other offending substances by blowing down the boiler, and (2) the introduction of castor oil into the boiler water. The first remedy is efficacious in about the extent to which the concentration of the offending substances in the water are reduced. Such a relation is so obvious that no theoretical discussion is needed. It is equally obvious that there is a heavy loss of energy in wasting water that has been heated to the temperature of the boiler, and therefore blowing down has severe limitations. Finally, the plan has no effect when the foam producing impurity is in the raw water.

Remedy No. 2, the use of castor oil, is perhaps the most interesting and effective treatment applied to industrial water. Its effect on the stabilized foams resulting from dissolved salts and suspended solids is like a touch of magic. A mere trace of this oil, less than 0.001 per cent by volume, causes the instant disappearance of the type of foam referred to above.

In actual practice castor oil is seldom or never used as such because it is not miscible with water and therefore difficult to apply in a uniform way. The general procedure is to prepare an anti-foam compound by emulsifying the oil with starch and other ingredients to give a mixture containing 14 to 15 per cent of oil. This will mix uniformly with a large quantity of even cold water so that the introduction of any desired amount into the boiler is easy.

On one of the Ohio railroads the rule[13] is not to begin using anti-foam till the boilers begin to foam, which usually takes place when the concentration of dissolved solids reaches 3000 parts per million (175 grains per gallon). A pint of anti-foam compound, containing 16 per cent of castor oil, is then put into the tender tank, which holds 5000 gallons of water. This would mean a concentration of less than 4 parts per million (about 0.2 grain per gallon) of actual oil in the water, and yet by its use the boiler can be kept going till the concentration of dissolved solids reaches double the value given above.

This effect of castor oil in inhibiting foam is apparently confined to that type of foam in which the films are stabilized by suspended solid matter. "Apparently" is used advisedly because the matter has never been systematically studied. A few experiments in the author's laboratory seemed to show, for example, that the oil had no effect on a soap foam.

A few other oils also inhibit foam as castor oil does, but for one reason or another have never come into use. Bardwell[14] found that pine-tar oil worked satisfactorily up to 140 lb. pressure, but not beyond. Incidentally, it might be remarked here that during the World War many experiments were probably made in search for substitutes for castor oil as an anti-foam. If this is true they ought to be recorded somewhere.

There is little or nothing on record concerning the prevention of foaming due to dissolved vegetable matter. French[15] found that alum served to prevent the foaming caused by dissolved vegetable matter in a highly colored Florida surface water. This is interesting because the generalization is perhaps warranted that such foam-producing substances can be rendered harmless by adsorbing them on precipitated aluminum hydroxide.

When the question of a physico-chemical theory of the destruction of foam by castor oil is raised, the answer must be, there is no theory. One may guess that the action is due to the destruction in some way of the stabilizing action of the suspended solids rather than to any effect on the liquid films. Perhaps the best way to get suggestions on this point is to study the data of ore flotation. Edser's paper (Footnote 11) in this connection is admirable.

FOAMING AND PRIMING AS A RESEARCH PROBLEM

Since the underlying purpose of this paper was to suggest points of attack in research work on the problem of foaming and priming of boiler water, it will be worth while now to classify the suggestions offered above. They fall naturally into two groups.

I Research with the object of finding the fundamental causes of foams and stabilized films in such water solutions as may occur in a steam boiler. This is a laboratory problem calling for measurements of surface tension, surface concentration, and viscosity, thickness of liquid films, angles of contact between solids and liquids, and long, patient experimentation with one combination of materials after another. Coincident with the above will be a line of experimentation with autoclaves or small experimental boilers.

This is the kind of work that is adapted to university surroundings in which the necessary scientific instruments, books, and journals are to be found.

II Research involving experiments with actual steam boilers under working conditions. This is preëminently the point at which the practical man comes in, and it is fortunate that the organization of the committees having this work in charge (Footnote 3) includes practical as well as theoretical men. The prospects for coöperation are fine.

There is of course no reason why these two groups of research should not mix in any proportion that circumstances may bring about, and it is certainly the wish of the author of this paper that they should be so mixed.

[13] Personal communication from C. P. Hoover.

[14] R. C. Bardwell. Personal communication to the author.

[15] D. K. French. Personal communication to the author.

Embrittlement of Steel

Progress Report of Sub-Committee No. 6 on Embrittlement of Metals*

By PROF. ALEXANDER G. CHRISTIE, BALTIMORE, MD., CHAIRMAN

THE WORK of this Committee has been confined to the consideration of the embrittlement of steels used in steam boilers. This subject has been receiving much study both here and abroad and many conflicting views have been submitted to the Committee for consideration. These have been carefully considered and analyzed.

There are two schools of thought in regard to this subject. Certain engineers, after studying embrittlement from many angles, have been led to the conclusion that such embrittlement as occurs is inhibited by the presence of caustic in the waters in the boiler resulting from the occurrence of sodium carbonate in the feedwater. Other engineers also, after careful study of the phenomena, have concluded that other causes contribute to this type of failure and that the presence of caustic is not the controlling factor.

This report will summarize the evidence and reasoning of both schools of thought and will attempt thereby to give engineers a definite idea of the problems involved. The Committee does not believe, in view of the data before it, that it is possible at the present time to reach any final conclusions regarding the cause and remedy of this trouble. Certain facts seem to be established and these will be presented. The Committee also makes certain recommendations at the close of its report.

The following outstanding facts are presented as indicating the present status of knowledge of the phenomena:

(*a*) Embrittlement of boiler metal is an established fact and not a myth as believed by some engineers.

(*b*) The difficulty has not been encountered in any one section of the country although there are certain areas where failures of this kind have been more prevalent.

(*c*) In most cases where these failures have been experienced, the water has contained relatively high concentrations of carbonate, bicarbonate or hydrates of soda and these waters have been low in sulphates or chlorides of soda. Some cases of embrittlement of boiler metal have occurred, however, with waters where the concentration of sodium salts was low.

(*d*) Embrittlement is a function of excessive stresses in the metal, and the phenomenon apparently does not occur in the absence of stresses beyond the elastic limit for the metal.

(*e*) It has been shown experimentally that embrittlement of boiler steel may be produced at will in the presence of excessive amounts of hot caustic soda (20,000 grains per gallon) when the metal is under tension beyond the elastic limit. The phenomenon takes place usually by the combined action of high stress and high chemical concentration. These facts have been established by laboratory experiments but the element of time affecting the phenomenon has not been established.

(*f*) Laboratory experiments and experience in practice indicates that the embrittlement of the metal may be inhibited by maintaining a specific ratio between the sodium carbonates and sulphates present in the water.

(*g*) Failure of the metal progresses by intercrystalline fracture. In practically all cases there is no deformation of the grains.

(*h*) One investigator has determined that a similar phenomenon may be produced by calcium nitrate.

Various investigators are by no means in accord concerning the basic cause or causes of the phenomenon, and much discussion has arisen as a result of the two schools of thought. There are certain points, however, upon which there seems to be general agreement. These are as follows:

(*a*) Brittleness of boiler steel may occur in the presence of high concentration of caustic soda and result from straining the metal beyond the elastic limit.

(*b*) Failures of this kind are intercrystalline in character.

(*c*) The cracking of metal occurs in practically all cases along the line of the rivets and on the dry side of the plates.

Certain investigators believe that the brittleness of metal is affected by the absorption of cathodic hydrogen, and that the rapidity of the action is accelerated by stresses in the metal. This view has not received universal acceptance.

Still others hold that embrittlement is due to the presence of such impurities as iron sulphide at the grain boundaries, which are dissolved by the action of caustic soda or other chemicals.

Some engineers believe that embrittlement is due partly to certain inherent characteristics of the steel and partly to stresses from deformation and riveting in the process of manufacture augmented by the stress due to the working pressure in the boiler. Evidence has been submitted to confirm this view.

A Review of Investigations and Opinions on Embrittlement

As early as 1866[1] Graham made the interesting discovery that red-hot iron was penetrated by hydrogen and that a portion of the hydrogen was retained by the metal after it had cooled down. Caillet[2] and Johnson[3] arrived at a somewhat similar conclusion and demonstrated that hydrogen generated electrically was absorbed by iron at room temperatures. They showed further, however, that hydrogen in a gaseous form apparently had no effect upon the metal. In Johnson's work it was shown that soft iron became embrittled in contact with electrolytic hydrogen. It was further shown by Johnson that the treatment of the iron with acid, prior to contact with the gaseous hydrogen, greatly accelerated the rate of embrittlement of the metal. It was reported by Thompson[4] that fairly high concentrations of solutions of soda at boiling temperatures had no appreciable effect on the properties of soft iron. It was also shown by the same investigator that soft iron was much more seriously affected by boiling water. Somewhat similar results were obtained by T. S. Fuller.[5] This investigator showed that the rate of absorption or penetration of hydrogen through a sample of electrolyzed iron was practically the same with one per cent caustic soda as when tap water was used. W. D. Andrews reported the results of experiments in the Transactions of the Faraday Society, 1914, stating that strips of steel kept in concentrated sodium hydroxide solution at 212 deg. fahr. for a period of from one to seven weeks were seriously embrittled. Hydrogen was evolved as the result of the action of the caustic soda. Most widely quoted experimental studies on this subject are those of S. W. Parr,[6] published in the University of Illinois

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* The personnel of Sub-Committee No. 6, on Embrittlement of Metals of the Joint Research Committee on Boiler Feedwater Studies is as follows:

Alexander G. Christie, *Chairman*, Professor of Mechanical Engineering, Johns Hopkins University, Baltimore, Md.

Samuel B. Applebaum, Assistant Technical Manager, The Permutit Company, 440 Fourth Avenue, New York, N. Y.

A. S. Behrman, International Filter Company, 333 West 25th Place, Chicago, Ill.

John H. Buell, Manager of Operations, Oklahoma Power Company, Tulsa, Okla.

R. E. Coughlan, Chicago and Northwestern Railroad, Chicago, Ill.

D. K. French, Dearborn Chemical Company, 310 South Michigan Avenue, Chicago, Ill.

John Hunter, Dr., Mechanical Engineer, 805 Merchants-Laclede Building, St. Louis, Mo.

J. B. Romer, The Babcock and Wilcox Company, Bayonne, N. J.

Albert E. White, Professor, Director, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

R. S. Williams, Professor of Metallurgy, Massachusetts Institute of Technology, Cambridge, Mass.

[1] Proceedings of the Royal Society, vol. 17, p. 219, 1869.

[2] *Comptes Rendus*, vol. 80, p. 319, 1875.

[3] Proceedings of the Royal Society, vol. 23, p. 186, 1875.

[4] Journal of Society of Chemical Industry, 1894.

[5] Transactions of the American Electrochemical Society, 1919.

[6] University of Illinois Bulletin, January 1, 1917, no. 94, and June 22, 1926, no. 155.

Note: Engineers interested in embrittlement should study carefully the last bulletin (no. 155) of Parr and Straub.

Be sure to bring this copy with you to the Annual Meeting

Bulletins in 1917 and by Parr and Straub in 1926. The conclusions reached by these investigators are as follows:

(*a*) Embrittlement in boiler plate is caused by the combined action of stress and chemical attack. The stresses are inherent in the construction and in the operation of the boiler, while the chemical attack is caused by sodium hydroxide in the boiler water.

(*b*) Certain methods of water treatment tend to convert some safe waters into the characteristic type of water which produces embrittlement.

(*c*) The presence of sodium sulphate in the feedwater and undecomposed sodium carbonate in the boiler water tends to retard the embrittling effect of carbonate waters, and if these are present in proper proportions they will stop it entirely.

(*a*) Methods for introducing sulphates in boiler waters have been worked out to the point of practical application.

R. S. Williams and V. O. Homerberg report in the Transactions of American Society for Steel Treating, April, 1924, the results of their experimental studies carried on at the Massachusetts Institute of Technology. The conclusions of these investigators are as follows:

(*a*) During the crystallization of steel, the impurities, to a considerable extent, are rejected to the grain boundaries.

(*b*) The oxides and sulphides are two of the prime factors in caustic embrittlement.

(*c*) The oxides are reduced under the influence of cathodic hydrogen.

(*a*) The sulphides are removed due to the action of hot caustic soda solutions.

(*e*) The removal of the sulphides produces a surface condition favorable to progressive corrosion.

(*f*) Assuming that progressive corrosion starts with the removal of the sulphides, the corrosion will be greatly accelerated if the material is stressed. Furthermore, when the steel is under tension there is a tendency for the matrix to pull away from the inclusions at the grain boundaries and in this manner to produce small capillaries into which the corroding solution can penetrate.

(*g*) In stressed areas containing oxides, the volume increase, due to the reaction with cathodic hydrogen, may produce stresses which, added to those initially present, may cause cracking.

(*h*) It seems evident that hydrogen acts in three ways to produce embrittlement: first, the temporary brittleness caused by absorbed hydrogen (as in acid pickling), second, it acts to reduce oxides, and third, its effect due to the change in volume at the grain boundaries, resulting because of the production of water. This latter volume increase would create a stress which, added to those originally present, may cause cracking, especially at those points where these stresses are at a maximum.

The 1922 Report of the Prime Movers Committee, National Electric Light Association, on Treatment of Feed Water in discussing this phenomenon, gives the general characteristics present in the embrittlement of boiler plate as follows:

(*a*) Occurrences ordinarily limited to the joints of the boiler.

(*b*) Occurrence only in parts of the boilers reached by the water. This is most noticeable in girth joints, as up to the place reached by the water (not necessarily the normal water line), cracking is found, and beyond that point the plate is unimpaired.

(*c*) Occurrence in the various members of the joint; that is, in the rivets as well as the plates, in both plates of a lap joint, or in plates and straps of butt joints.

(*a*) Occurrence in rolled plates, cast steel or cast iron, according to the construction of the boiler.

(*e*) When a plate is cracked, the line of the crack on the surface of the plate in contact with the surface of another plate is longer than the line of the crack on the other surface of the same plate (i.e., embrittlement starts at the surfaces in contact).

(*f*) Extreme irregularity of the cracks with sharp changes of direction; paralleling without any marked tendency to join; in other words, the exact position of a crack is not determined by the stress due to the boiler pressure, though the general area affected may be

(*g*) Brittleness of the material under shock and fatigue, with very little indication of brittleness under static tests, and marked localization of the embrittlement to the joint area.

(*h*) Loss of embrittlement (not necessarily total) with time when the boiler is removed from service, coupled with a marked degree of removal of embrittlement by heating at temperatures far below those required for ordinary annealing.

(*i*) A plentiful deposit of a black, powdery substance on the affected surface which on analysis is principally an iron oxide.

Since the location of cracking of this sort is selective with respect to the parts of the seams reached by the water of the boiler, reference should be made to the feed conditions and apparently with the following conditions in mind:

(*a*) Solubility will be of prime importance for the reason that a highly soluble substance may be present in heavy concentration without depositing anything on the metal to mechanically protect it.

(*b*) These substances should not attack the metal in the concentration in which they usually occur in a boiler, but should attack the metal in the higher concentration that can build up in restricted areas like the boiler joints.

(*c*) Acids can be eliminated from consideration, as they attack the entire metal surface at any concentration that could occur in boiler practice.

(*d*) Substances of high specific conductivity would increase the corrosive effects resulting from potential differences in the boiler structure.

(*e*) Substances such as calcium and magnesium carbonates, calcium sulphate, etc., being incrusting salts and of low specific conductivity, may be eliminated from consideration for either reason alone.

The soluble salts generally found in practice are given in the following table, Column "A" showing solubility in grams per 100 cc. of water at 100 deg. cent., Column "B" showing equivalent conductivity at 18 deg. cent.:

	"A" Solubility	"B" Conductivity
Sodium Chloride	39.12	92.0
Magnesium Chloride	73.0	98.1 ($\frac{1}{2}$ $MgCl_2$)
Calcium Chloride	159.0	88.2 ($\frac{1}{2}$ $CaCl_2$)
Sodium Sulphate	42.5	78.4
Magnesium Sulphate	73.8	76.1 ($\frac{1}{2}$ MgS_4)
Sodium Carbonate	45.5	72.9
Sodium Hydroxide	339.0	203.4
Potassium Hydroxide	178.0	228.0

NOTE: Potassium hydroxide, while of most exceptional occurrence, is included on account of the values of its constants as compared with sodium hydroxide.

From this table, sodium hydroxide has the greatest index of solubility and conductivity. Sodium chloride is relatively low in both solubility and conductivity, and by itself is not known to be corrosive under boiler temperatures at any concentration. Magnesium chloride and calcium chloride, while higher than sodium chloride in solubility and conductivity, have hydroxides that are very low in solubility, and corrosion from these substances occurs even at low concentration on all exposed surfaces. Hydrolysis of sodium carbonate is very considerable under boiler temperature, and within the range of usual boiler concentration in its effect it may be regarded as though it were sodium hydroxide. Sodium sulphate will ordinarily occur in boilers as the result of the initial use of sodium carbonate, so that for all of the foregoing reasons sodium hydroxide should (*a priori*) be considered as the most probable cause of the trouble. It is to be noted also that sodium hydroxide is only very slightly corrosive at boiler temperatures in solution strengths such as occur in the main body of the water in the boiler, but is actually highly corrosive in the stronger solutions that can occur in the joints.

F. B. Porter[7] has drawn the following conclusions from the results of his studies:

"At the University of Illinois, boilers had been operated intermittently for twelve years at 100 lb. pressure on the soft alkaline water without trouble. Three years' operation at 140 lb. pressure put four drums out of service, and we judge that there were four drums that withstood this same operation that were still unaffected. There is a large number of boilers at Fort Worth, Dallas, Waco, McKinney, Houston, Baton Rouge, Louisiana, and other points

[7] Paper read before the American Chemical Society, Tulsa, Okla., April 5, 1926.

that have been operating on soft, alkaline water on pressures from 150 to 210 lb. that have never shown indications of embrittlement. The Trinity sands water in Texas contains enough sulphates to give a sulphate ratio of something like three of sulphates to one of alkalinity, but the other artesian waters used at the plants just mentioned have much less sulphates, some of them only a very small amount. In one plant at Dallas, two plants out of four at Houston, and at one Waco plant an occasional drum has been lost through embrittlement, and in practically every case other drums which have seen the same service with the same water are still in operation, and other plants using the same water have never been affected.

"The question of the contributing causes of this peculiar type of embrittlement is important in suggesting remedies and in adjusting a settlement on installations on which renewals are required. This trouble occurs often within six months to three years of the time the boilers are put in service. The cracking occurs in regions of little stress. The actual stress in boiler operation in butt-strap seams is small compared with other sections of the drum. The stresses in the metal set up in the fabrication of the drum in the area adjacent to the rivets may be high. It is a difficult question to decide whether boiler-water leakage into the seams evaporates and produces high concentration and starts embrittlement, or whether the embrittlement and cracking start and the leaks promptly result therefrom. If the leaky condition comes first, it probably does not make very much difference what the concentration of the boiler water is, for the reason that a concentration even to the solid can rapidly occur in the seam as soon as the leak starts.

"The impression has been general that it is only overtreated, softened waters that would be likely to cause embrittlement. A recent case of embrittlement where zeolite-treated water only had been used would indicate that any softened water may furnish one of the requisite causes for embrittlement. The mention above of pressures obtaining in boilers and intermittent operation as compared with continuous operation, leads us to make the general observation that we believe that higher pressures and more continuous operation tend to increase the likelihood of embrittlement taking place, but this is as strong as this statement can be made, for some boilers operating under the same pressure and on the same water may be affected and some of them not. One hundred and forty pounds at the University of Illinois, which caused the loss of four drums, is considered a very low water pressure on large plants today.

"In conclusion, it seems at the present time that the only explanation of caustic embrittlement that will account for this condition being present in some drums of some plants and absent in other drums of these same plants, and absent in all the drums of other plants, using the same waters and the same type of waters, is that embrittlement is due to overstrained or dirty steel and causticity in contact with same."

Mr. McAdam of the U. S. Naval Engineering Experiment Station in a discussion of Professor Parr's paper at the 1926 meeting of the A.S.T.M., reported that he produced intercrystalline cracks in specimens subjected to fatigue tests when he cooled them during the test by directing a jet of water against the specimens.

Mr. Patterson of the Solvay Process Company in a discussion of Professor Parr's paper (loc. cit.), pointed out that caustic soda cannot concentrate very appreciably within the interstices of a seam as long as the seam is tight, since the boiling temperature of a more concentrated solution is higher than that of a more dilute solution, so that as soon as a concentration of the caustic soda solution within the seam rises above that of the main body of water in the boiler, further concentration in the seam stops, since no further evaporation will take place. Therefore it will be impossible to concentrate the solution within the seam to the degree found active by Professor Parr, as long as the seam does not leak. Mr. Patterson has directed attention to the possibility of oxygen in the water as a possible offender accelerating embrittlement.

Mr. Applebaum of the Permutit Company has quoted the work of Mr. Jones:[8]

"In a fresh solution, stressed steel cracked in a few days, but after the solution had been in use for some time the steel became coated with a black deposit of oxide and cracking was inhibited. This is not solely due to the alteration of surface of the steel since the solution now fails to crack fresh similar specimens which are introduced and which themselves become coated much more quickly than the original specimens. A deposit consisting of magnetic oxide and some carbonaceous matter accumulated at the bottom of the vessel. The inhibiting effect of the presence of oxide lends support to the view that cracking is brought about through the agency of hydrogen."

As a result of the experience and extensive experimental work of the Babcock and Wilcox Company, the following conclusions have been drawn by the company concerning this phenomenon and are reported in the 1925–26 Report of the Prime Movers Committee, N. E. L. A. on Treatment of Feed Water.

Certain characteristics of this cracking are as follows:

1 The cracks all occur below the water level.

2 In at least one of these plants, cracking of boiler drums has continued over a period of at least twelve years. In some cases, replacement drums cracked in a shorter period of time, notwithstanding special care in manufacture.

3 All of these cracks have occurred in seams under tension, having factors of safety, as normally calculated, from five to approximately ten.

4 Examination of the type of plate showing cracks has definitely shown that this cracking occurs in plates having practically perfect chemical and physical characteristics, as well as in plates which may not have as good characteristics.

5 These cracks have developed in cast steel, steel boiler plate and the most perfect rivet steel.

The characteristics of the cracks themselves in general are:

(*a*) They do not follow the line of maximum stress.

(*b*) While in general they run from one rivet hole to another, they run more often in entirely different planes, so there will be a crack from one rivet hole passing parallel to a crack from another rivet hole.

(*c*) They frequently run from each of two adjacent rivets past each other for at least half their length without joining, or they even cross the full ligament from rivet to rivet without joining, leaving little islands of plate.

(*d*) They are irregular in direction when fully developed, having numerous sharp angles, and the final direction of the cracks is sometimes 90 deg. from that at their beginning.

(*e*) They never extend into the body of the plate beyond the lap of the plate.

(*f*) They sometimes occur on the solid plate of the seam and do not connect with the rivet holes.

(*g*) The cracks are not accompanied by elongation of the plate.

(*h*) Photomicrographs of these cracks indicate that they are intercrystalline.

(*i*) The cracks start on what is usually termed the "dry" face of the joints.

(*j*) As stated before, the cracks all occur below the water level of the boiler.

The 1925–26 report of the Prime Movers Committee, National Electric Light Association on Treatment of Feed Water, contains a statement by the Permutit Company in which they summarize the factors that enter the problem, as follows:

"In our opinion there are four factors which must be considered in tracing the origin of cracks in boilers:

(*a*) The quality of the steel.

(*b*) The stresses either existing in the plate before fabrication, or introduced during fabrication, operation and repair, in addition to the calculated working stresses.

(*c*) The temperature to which the steel is exposed when under the total stress and the period of time during which the total stress is acting.

(*d*) The composition of the feedwater as well as the boiler salines."

A number of interesting comments have been received, some of which are reported herewith. The president of a firm manufacturing chemical machinery in a letter to the Chairman states as follows:

"In the manufacture of caustic soda we find that the eventual failure of what is known as a caustic soda pot is probably due to

[8] Transactions of the Faraday Society, vol. 17, p 149.

the continued heating and cooling of the cast-iron pot rather than to definite caustic or chemical action. It is true that we do have some of this caustic or chemical action, but the industry seems to agree fairly well that the reason for the final destruction of caustic soda pots is that continuous heating and cooling of the vessel itself bears the greatest burden of the failure of the casting."

A leading consulting engineer in a letter to the Chairman states:

"The full nature of conditions tending to cause caustic embrittlement is far from definitely determined. The evidence while pointing to existence of caustic in solution as probably the most frequent cause, would indicate, however, that caustic by no means occupies a unique position in that respect."

A prominent chemical engineer writes as follows:

"I fail to find any direct tie-up between the character of the water and embrittlement. Such tie-up as does exist is based very largely on 'hunches,' and not on any real data. That is, we know that certain of the water analyzed is poor water for boilers. We deduce, therefore, that this water will produce caustic embrittlement. We examine the boilers and we find cracks and fractures. The boiler even in certain sections may manifest considerable brittleness. We put the two things together and reach the conclusion that the boiler feedwater has been responsible for the cracks and other failures, through the action of caustic embrittlement. Such reasoning may be correct. It does, however, lack the continuity of proof, which we, as engineers, should demand."

An interesting case of embrittlement in a pressure vessel normally containing hot caustic soda in rather high concentrations, was recently called to the attention of the Chairman. This case was very thoroughly investigated and the conclusion reached that the failure was apparently due to the structure of the plate itself at the time it was fabricated. Microscopic examination showed an almost perfect Widmanstaetten structure (a structure usually formed in cast steel) in the cross-section of the metal. In view of the inherent weakness of this structure, it is doubtful whether the caustic had any influence in causing the failure of the shell.

A leading British metallurgist who has devoted much study to this subject and from whom the Committee requested a statement, has written the Chairman in a private communication as follows:

"I do not know of any recent publication in this country bearing on the matter, but I have followed with interest what has been done in America and Germany. With regard to Professors Parr and Straub's paper, I have read it with very great interest and appreciation. While I find some difficulty in believing that a concentration as high as their experiments suggest, can ever be produced in a boiler, even in the fissures or seams, and while I also think that a stress exceeding the yield point can only be caused by the existence of severe local stresses due to excessive riveting pressure, etc., I yet feel that their present work has put the matter on a sounder basis than formerly. Their experiments appear to me to establish the fact that caustic soda when sufficiently concentrated can act as an accelerator of cracking in heavily stressed steel. Whether this can be regarded as by any means a full explanation of what occurs in boiler practice, is quite another matter and remains to be established by further work. The only light that I can throw on the whole question is that, so far our experiments—made with a view to producing fracture under prolonged loading in mild steel stressed to various intensities at a temperature of 300 deg. cent. in air—have failed to produce fracture even after a number of years' exposure. This experiment certainly suggests that some subsidiary agency of a corrosive nature is necessary to produce failure in a reasonable time, although it is quite possible that the particular sample of steel which I employed was not one subject to intercrystalline fracture under prolonged loading. There is to my mind no doubt at all that the nature and condition of the steel plays a large part in the matter.

"The only immediate suggestion I can offer is that experiments on the lines of those made by Parr and Straub should be carried out on steels of different origin, particularly on acid as well as basic steels and after various forms of heat treatment, including a heat treatment which shall render the carbide granular or spherulitic instead of lamellar."

A consulting engineer of prominence who has had over forty years' experience in chemical and mechanical engineering, has furnished the Committee the following opinion relating to the problem of embrittlement.

"The cases of embrittlement which have come under my observation have been so contradictory that I am led to believe that only certain qualities of steel are affected. By quality I mean physical quality. The chemical analysis seems to throw no light on this subject, and in the same apparatus one sheet of steel will develop minute cracks, which in many cases are in the middle of a sheet, while other sheets in the same apparatus and under the same conditions, last indefinitely.

"I have never known any case of embrittlement in boiler shells or steam drums of boilers, except with very concentrated liquors. I once tried the use of a water-tube boiler for concentrated caustic liquor from 20 to 30 deg. B. These boilers gave no trouble while in this service for a period of several months, but after being returned to ordinary boiler service, I found one of the seams of one of the drums had a crack along the calking of the longitudinal seam nearly three feet long, and the inside had a number of minute cracks extending from one rivet hole to the others, sometimes in two or three directions. This seam was cut out, taken apart and examined very carefully. The water was being treated with soda ash and lime and contained a small amount of caustic soda which was, however, not allowed to concentrate very much, but it was evident that if the water could leak into the space between the laps which were not very well drawn together, the caustic might concentrate in that particular seam and have an action on the steel which would not be possible with the low concentration.

"Following this were several others of a similar kind, where the drums had been used for concentrate caustic liquor and cracks were found by examination with a microscope in a number of other drums, always in the seams between rivet holes where the joints had been pulled together with drift pins, or where the severe calking had been done.

"I have also noticed that steel tanks containing hot 40 deg. B. liquor are gradually embrittled, especially in the seams. When struck with a hammer, after these tanks have been long in use, the rivet heads will pop off, showing in many cases cracks which are part way through the rivets, which had evidently been there a long time, but alongside of them were other tanks with 20 deg. B. liquor that had been in use for 35 years, some of them wrought iron, some steel, which were not affected.

"I have noticed in some cases where cast-iron pipe joints are held together with bolts and slight leaks of caustic liquor occurred, which ran over the bolts, that these bolts were broken in two in two places, or many of them half-broken in two. In one case of a large B. & W. "W"-type boiler, a lower drum developed some cracks in one sheet. Six other boilers running under the same conditions gave no trouble. A spare drum was ordered which has never been put in, and while the failure was laid by the manufacturers to embrittlement, and several learned reports were written on the subject, I have never been satisfied that the cracks were caused by the very slight amount of caustic soda present in the water."

Professor Baumann in a lecture before the Association of Steam Boiler Inspectors at Zurich, Switzerland, on September 7, 1926, stated that the evidence from laboratory tests indicated that the presence of caustic soda is not essential to the formation of intercrystalline cracks.

Dr. Guilleaume in a recent report[9] stated that in all cases where steel failed in service, the failures were traced to thermal and mechanical causes. In no instance was it indicated that caustic soda had been responsible for the development of the fracture of the metals.

Last year, two important[10] contributions on this subject appeared in Germany. Dr. Bauer, of the Metallographical Institute of Dahlen, has shown that hydrogen in contact with metal and under high pressure (up to 3000 lb.) will not affect the strength of the metal when the contact takes place at room temperatures. Dr. Bauer has demonstrated, however, that relatively small amounts of hydrogen in contact with iron or steel at boiler

[9] Report presented to the Association of Large Steam Boiler Plants at Cassel, Germany, Sept. 17, 1926.

[10] Papers read at the Association of Owners of Large Boilers at Darmstadt, December, 1925.

temperatures is readily absorbed by the metal, materially reducing its tensile strength.

Professor Thiel's research studies have shown that 77.5 per cent of caustic soda may concentrate in the clearances between the boiler plates, resulting in reducing the tensile strength of the boiler. This action, according to Professor Thiel, is due to the absorption of hydrogen which is released from the caustic soda when the sodium unites chemically with the iron.

An enlightening editorial on the subject of embrittlement appeared in *Power* in the August 17, 1926, edition of this periodical. A portion of this comment is quoted since it confirms the Committee views that future research is highly desirable.

"Are there not several kinds of causes for embrittlement? Are all embrittlement cracks from the same cause? The boiler user is intensely interested in the answers to such questions.

"But the boiler user cannot be content to sit idly awaiting the conclusions of what is to him in a measure an academic question. After all, he cares little by what name his trouble is called. His demand is for some remedy that will enable him to operate safely. Whether the remedy is scientifically rational or purely empirical is interesting, but not vital to him. Even a 'hunch' is good enough for him if it works. True, there may be a cheaper and better way to be developed through further research, and this the operator wants, but he dare not wait for it. He must do something now.

"What shall he do? Two factors are involved—stress and water conditions. Perhaps the elimination of either alone will cure the disease, but since both are under suspicion, why not do all that can be done to eliminate both? Severe internal stress is admittedly bad on all counts. Let every effort be made to eliminate it by insisting on first-rate material and the best possible shop practice. Certain materials in solution in the feedwater seem also, in some instances at least, to be a contributing cause. Let care be taken in adding such things to the water or in neutralizing them if they are already present."

Your Committee has attempted to summarize the work of the various investigators and to present the viewpoint of those who have advanced the theory of embrittlement due to high concentrations of caustic soda and that of those rejecting this premise. The latter call attention to the following phenomena which may influence the failures.

Gaseous hydrogen from any source may penetrate steel and be occluded by it, resulting in embrittlement of the metal. This phenomenon may take place not only from caustic soda but from any other source. Excessive strains set up in the metal may be the primary cause for embrittlement and the source of intercrystalline cracking. Intercrystalline cracks may be developed in ferrous and non-ferrous metal due to improper thermal treatment in the manufacture of the metal.

The advocates of caustic embrittlement tend to direct attention to the quality of water as the offending agent rather than the material in the boiler or the method of fabricating the equipment. Failures of this kind have occurred largely in certain sections of the country where the water used for boiler feed contains relatively large quantities of sodium carbonate and bicarbonates and is low in sulphates or chlorides. In many instances, the difficulty has disappeared entirely by changing the source of the feedwater and using water that did not have these characteristics or by treating the water chemically so as to maintain a predetermined ratio between the carbonates and sulphates.

The difficulty has not been confined to boilers of any one manufacturer, thereby tending to eliminate the theory of faulty design and construction or dirty metal. Embrittlement of metal has been produced by investigators by duplicating conditions that theoretically should be favorable to producing the characteristic intercrystalline cracking of the metal.

A complete bibliography of the subject of embrittlement of metals has been prepared by the Engineering Library, 29 W. 39th Street, New York, copies of which can be secured for a nominal charge by any one interested in this subject.

RECOMMENDATIONS

Most of the experimental work which has been carried on has been with waters high in carbonate or bicarbonate of soda. Little information is available concerning the possibility of embrittlement of boiler metal in waters low in these salts. It has already been demonstrated in one case reported to the Committee that embrittlement of boilers may and has resulted from the use of feedwater low in sodium salts.

Little information is available concerning the effect of dissolved gases in accelerating the phenomenon of embrittlement.

High pressure as a contributing agent has not been established. There are many other factors entering into the problem which up to the present time have received no special attention from investigators of these problems. It is evident that there is much still to be learned concerning the cause or causes of intercrystalline cracking of boiler plate and much is to be learned concerning the methods of controlling the contributing factors.

The preceding paragraphs present a brief digest of the great mass of data submitted to the Committee. A careful study of all of this material has led to the formulation of the following recommendations:

(1) In view of the wide diversity of opinion on the cause of embrittlement, extensive research should be started to determine the influence of all possible contributing factors.

(2) Plans for such research should be formulated to give cognizance to causes of embrittlement other than those which may result from the use of waters in which high concentration of caustic soda is potentially possible.

(3) Not only must the causes of embrittlement be determined but means of preventing its occurrence under all conditions should be developed as soon as all contributing causes are known.

(4) Since the plate ligament or the rivets in riveted joints may be stressed beyond the elastic limit of the metal, a study of other means of joining plates such as welding, is a logical step in the elimination of embrittlement troubles.

(5) This research may be carried out in University laboratories but funds must be obtained to finance this experimental work.

(6) This Committee should be continued to coördinate the research work and to report developments in the study of Embrittlement of Metals.

Municipal Water Supplies and the Effect of Trade Wastes in Relation to the Use of Water in Power-Plant Practice

Progress Report of Sub-Committee No. 7 on Municipal Water Supply in Relation to Boiler Use[1]

BY V. BERNARD SIEMS, BALTIMORE, MD., CHAIRMAN

THE activities of this Committee during the past year have been devoted to two distinct problems affecting the treatment of water for steam-making uses and for condenser purposes.

(*a*) Collection of data relative to the quality of water supplied by municipalities and its effect on the cost of operation of industrial water treatment systems

[1] The personnel of Sub-Committee No. 7, on Municipal Water Supply in Relation to Boiler Use, of the Joint Research Committee on Boiler Feedwater Studies is as follows:

V. BERNARD SIEMS, *Chairman*, Water Engineer, City Hall, Baltimore, Md.

W. R. ABBOTT, Chief Engineer, Commonwealth Edison Company, Chicago, Ill.

A. J. AUTHENREITH, Vice-President, Middle West Utilities Company, Chicago, Ill.

EDWARD J. BILLINGS, Mechanical Engineer, Henry L. Doherty and Company, 60 Wall Street, New York, N. Y.

JOHN H. BUELL, Manager of Operations, Oklahoma Power Company, Tulsa, Okla.

W. D. COLLINS, U. S. Geological Survey, Washington, D. C.

CHARLES FOX, Assistant Superintendent, Pennsylvania Water Company, Wilkinsburg, Pa.

C. P. HOOVER, Chemist and Superintendent, Water and Sewage Department, Columbus Filter Plant, Columbus, O.

NICHOLAS S. HILL, JR., President, Hackensack Water Company, Hackensack, N. J.

B. N. RANDOLPH, Water Purifying Department, William B. Scaife and Sons Company, Oakmont, Pa.

CALEB M. SAVILLE, Manager and Chief Engineer, Water Works, 53 North Beacon Street, Hartford, Conn.

(*b*) A study of the effect of trade wastes and domestic sewage discharged into surface streams used as a source of supply for power-plant uses.

Early last year a questionnaire was sent out to a large number of companies for information concerning these problems. The results of this inquiry indicated clearly that the treatment of municipal water supplies does not, in most cases, seriously affect its value for steam-making uses. There is a tendency, however, on the part of some municipal-water-treatment-plant operators to lose sight of the industrial users' requirements, provided the sanitary requirements for the safe quality of the water are fulfilled. This is indicated by the increasing popularity of the procedure of adding sulphuric acid to water prior to alum, to increase coagulation, and to the inhibition of corrosion by the addition of lime to the filtered water. There is apparently a complete lack of knowledge by most engineers responsible for the treatment of water for industrial use, concerning these conditions. There are no data available as to the effect of such treatment on the cost of operation of privately owned water-purification plants.

Preliminary studies by the Committee indicates that these problems are of sufficient importance to be given consideration and require further study.

Considerable apathy apparently exists concerning the detrimental effect of trade waste on the operation and maintenance of power-plant equipment. Excepting in certain areas, particularly in the Pittsburgh district and in some other districts, little effort has been made to cope with the problem.

One company situated in a highly developed industrial area has furnished the Committee with considerable detailed information concerning corrosion problems at its plant. A portion of their report is as follows:

"Our trouble has been due to acid coming from the pickling baths of a steel mill. This acid forms a hard oxide scale on the condenser tubes that seriously impairs our vacuum. This scale is so hard that the only effective method for its removal is the hydrochloric-acid-bath treatment.

"The acid in the water has eaten out our feed lines, impellers, strainers, etc. We are now just renewing completely the entire auxiliary feed lines. The old lines taken down were very badly eaten through, and all contained blisters and pockets."

The cost of cleaning the condensers at this plant is over $5000 yearly.

The effect of oil-refinery sludge on condenser operation is indicated in the following statement furnished by a large power company in the Middle West.

"The plant is located at a point below several oil refineries. These refineries discharge into the river certain oil sludges which carry acid. We have had to retube our condensers, and to date have not been able to determine whether the pitting or corrosion, which goes on in the condenser tubes, is due to the chlorine or alkaline character of the water or if it is assisted by the acid contained in the oil sludge, which latter substance deposits on the inside of the condenser tubes."

Replies from five companies using river water contaminated with oil sludge reported serious trouble from corroded condenser tubes, and reduced vacuum as a result of sludge accumulation on the inside of the tubes. Two reported priming and foaming of boilers as a result of oil although both companies used filters and softening plants to treat the feed water. At one plant the boiler-tube losses were excessive and these failures are traced directly to the presence of oil.

It is also quite apparent that domestic sewage, discharged into water courses used for cooling water in surface condensers, has a very detrimental effect. Several large companies on the Atlantic seaboard report that they can trace poor condenser efficiency and the majority of their condenser failures to this source.

The Committee submits this progress report merely to direct attention to the magnitude of the problem and makes the following recommendations:

(1) Continuation of the Committee and expansion and coöperation with various state and governmental bureaus which are giving consideration to these problems.

(2) Constructive research leading toward more efficient methods of treatment for the removal of trade waste from feedwater.

(3) A comprehensive study of existing laws and ordinances relating to the prohibition of trade-waste pollution of streams used for feedwater or cooling-water purposes.

The Committee has established relations with the Trade Wastes Committee of the American Water Works Association and has arranged for an interchange of data relating to these problems.

Progress Report of Sub-Committee No. 5 on Corrosion of Boilers and Effect of Treated Water in Accelerating or Relieving These Troubles[1]

BY FRANK N. SPELLER, PITTSBURGH, PA., CHAIRMAN

As a result of the symposium and general conference on corrosion in boilers held at the annual meeting of the A.W.W.A., June, 1926, it is the opinion of this Committee that the time has now arrived when work on the boiler corrosion problem should be centered in a Committee of this kind representing both locomotive and stationary boilers. It is particularly desirable to have the railroads well represented as their corrosive conditions are usually much more severe, and therefore offer more opportunity for study of the various factors involved. To accomplish this object the following procedure is suggested:

1 A thorough survey should be made of important work already done on boiler corrosion. This may involve the preparation of a condensed bibliography.

2 A laboratory study will be made of the important factors involved in boiler corrosion and of means for corrosion prevention. This phase of the work will include, for instance, a study of the influence of alkalinity combined with common salts and oxygen in solution and other variables. Such work should be done under boiler temperatures and pressures.

3 A supervised application will be made of the most promising preventive measures under various service conditions.

To carry out this program it will be necessary to obtain the full-time service of a technical man who has had previous experience in working out corrosion problems. This will involve some expense. The Committee is now considering this plan and ways and means by which it may be carried out, but at present nothing definite has been decided. Much valuable work has been done by individual investigators and important results in combating corrosion have already been obtained. We feel that at present it is of primary importance to carefully prepare a plan of investigation before undertaking any coöperative research of this kind.

The members of the group of engineers carrying forward this part of the program of research are listed in Footnote 1 below.

Progress Report of Sub-Committee No. 9 on Bibliography[2]

BY GEORGE A. STETSON, NEW YORK, N. Y., CHAIRMAN

THE Sub-Committee on Bibliography intends to provide to the technical Sub-Committees, to the Advisory Committee, and to the technical press selected items from the technical literature of current publications. The items will consist of the title, author, reference to publication, and a short note describing the contents of the article selected.

[1] The personnel of Sub-Committee No. 5 on Corrosion of Boilers and Effect of Treated Water in Accelerating or Relieving These Troubles, of the Joint Research Committee on Boiler-Feedwater studies is as follows:

FRANK N. SPELLER, *Chairman*, Metallurgical Engineer, National Tube Company, 1802 Frick Building, Pittsburgh, Pa.

R. C. BARDWELL, Superintendent, Water Service, Chesapeake and Ohio Railroad, Richmond, Va.

JOHN R. BAYLIS, Principal Sanitary Chemist, Montebello Filter Company, Baltimore, Md.

R. E. COUGHLAN, Chicago and Northwestern Railroad, Chicago, Ill.

MAX HECHT, Duquesne Light Company, Pittsburgh, Pa.

CLARENCE F. HIRSHFELD, Chief, Research Department, Detroit Edison Company, 2000 Second Avenue, Detroit, Mich.

ALBERT E. WHITE, Prof., Director, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[2] The personnel of Sub-Committee No. 9 on Bibliography of the Joint Research Committee on Boiler-Feedwater Studies appears at end of report.

The items of which the bibliography is composed are selected by the regular editorial staff of the Engineering Index, published by The American Society of Mechanical Engineers, and are sent monthly to the chairman of the Bibliography Sub-Committee. From these, the most significant items are chosen and put in mimeographed form for distribution through the courtesy of the A.S.M.E. To the items so selected are added items from *Chemical Abstracts* which may not have been found by the Index editors, and also book notices whenever these are available. The resulting bibliography should contain every item of importance published in this country and abroad.

The editorial staff of the Engineering Index reviews in a year more than 1300 periodicals, reports, and other publications received by the Engineering Societies Library.

The plan outlined above was put into operation about the first of October, 1926, and has the advantage of being almost automatic in operation as well as complete in the ground which is covered by it. A list of "key words" has been furnished the editorial staff of the Index so as to simplify for them the process of selection.

The group of engineers who are carrying forward this part of the program of research on boiler feedwater studies is as follows:

GEORGE A. STETSON, *Chairman*, Assoc. Prof., Heat Power Engrg., New York University, University Heights, New York, N. Y.

EDWARD BARTOW, Dr., State University of Iowa, Iowa City, Ia.

A. S. BEHRMAN, International Filter Company, 333 West 25th Place, Chicago, Ill.

A. M. BUSWELL, Dr., Director, Water Survey, Urbana, Ill.

FRANK HANNAN, Chemist, Filtration Plant, 285 Willow Avenue, Toronto, Ontario, Canada.

CLARENCE R. KNOWLES, Superintendent of Water Service, Illinois Central Railroad, 135 East 11th Place, Chicago, Ill.

PHILIP W. SWAIN, Associate Editor, *Power*, McGraw-Hill Publishing Company, 10th Avenue and 36th Street, New York, N. Y.

Progress Report of Sub-Committee No. 1 on Sedimentation with and without Chemicals, Pressure and Gravity Filters and Deconcentrators, Continuous Blow-Down Apparatus

(Report not received in time for publication)

The personnel of Sub-Committee No. 1 on Sedimentation with and without Chemicals, Pressure and Gravity Filters and Deconcentrators, Continuous Blow-down Apparatus of the Joint Research Committee on Boiler Feedwater Studies is as follows:

R. C. BARDWELL, *Chairman*, Superintendent, Water Service, Chesapeake and Ohio Railroad, Richmond, Va.

C. W. DEFOREST, Manager, Electric Department, Union Electric Company, 4th and Plum Streets, Cincinnati, O.

WELLINGTON DONALDSON, Consulting Engineer, Fuller and McClintock, 170 Broadway, New York, N. Y.

J. P. HANLEY, Inspector of Water Service, Illinois Central Railroad, Chicago, Ill.

B. N. RANDOLPH, Water Purifying Department, William B. Scaife and Sons Company, Oakmont, Pa.

Progress Report of Sub-Committee No. 4 on Surface Condensers, Evaporators, and Deaerators

BY PROF. A. E. WHITE, ANN ARBOR, MICH., CHAIRMAN

(Report not received in time for publication)

The personnel of Sub-Committee No. 4 on Surface Condensers, Evaporators and Deaerators of the Joint Research Committee on Boiler-Feedwater Studies is as follows:

ALBERT E. WHITE, *Chairman*, Professor, Director, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

EDWARD J. BILLINGS, Mechanical Engineer, Henry L. Doherty and Company, 60 Wall Street, New York, N. Y.

F. G. CUNNINGHAM, Fuller and McClintock, 600 Walnut Street, Kansas City, Mo.

HAROLD FARMER, Chief Chemist, Philadelphia Electric Company, Philadelphia, Pa.

JOHN HUNTER, Dr., Mechanical Engineer, 805 Merchants-Laclede Building, St. Louis, Mo.

J. H. MCDERMIT, Elliot Corporation, Jeannette, Pa.

ABBOTT L. PENNIMAN, JR., Superintendent, Steam Station, Consolidated Gas, Electric Light and Power Company of Baltimore, Lexington and Liberty Streets, Baltimore, Md.

FRANK N. SPELLER, Metallurgical Engineer, National Tube Company, 1802 Frick Building, Pittsburgh, Pa.

Progress Report of Sub-Committee No. 8 on Standardization of Water Analysis

(Report not received in time for publication)

The personnel of Sub-Committee No. 8 on Standardization of Water Analysis of the Joint Research Committee on Boiler Feedwater Studies is as follows:

HAROLD FARMER, *Chairman*, Chief Chemist, Philadelphia Electric Company, Philadelphia, Pa.

R. C. BARDWELL, Superintendent, Water Service, Chesapeake and Ohio Railroad, Richmond, Va.

VINCENT M. FROST, Assistant to General Superintendent of Generation, Public Service Gas and Electric Company, 80 Park Place, Newark, N. J.

MAX HECHT, Duquesne Light Company, Pittsburgh, Pa.

SHEPPARD T. POWELL, Chemical Engineer, 4103 Hawthorne Avenue, Baltimore, Md.

B. N. RANDOLPH, Water Purifying Department, William B. Scaife and Sons Company, Oakmont, Pa.

CYRUS W. RICE, Consulting Engineer, C. W. Rice and Company, 617 Highland Building, Pittsburgh, Pa.

Synopses of Other Annual Meeting Papers

THESE papers, abstracts of which are being published on this and the following pages, are being printed in full in pamphlet form for the Annual Meeting of The American Society of Mechanical Engineers. They may be secured by filling out either the blank on the last text page of this issue or that published in the November 7 issue of the A.S.M.E. NEWS and mailing it to the office of the Society. The remainder of the papers preprinted for the meeting are being distributed in this special Mid-November issue of MECHANICAL ENGINEERING. The tentative program for the Annual Meeting appears on pages 1193 and 1194 of this issue.

Laws of Manufacturing Management

By L. P. ALFORD

Vice-President, Ronald Press Co., New York, N. Y.

THE paper is divided into two parts, the first of which discusses the laws of management in general. It is stated that the principles of management have been discussed but not generally accepted, a situation which is in contrast with the older sciences. Early attempts to formulate these principles sought for a few statements, although certain facts indicate that there are many management fundamentals. The possible advantages of formulating the principles are pointed out and the questions are asked: What is their origin? What is their nature? What are they?

The investigation is limited to manufacturing management, inasmuch as management originated in manufacturing.

It is shown that manufacturing developed to satisfy human needs and that accepted ways for getting work done existed before manufacturing. Three such anciently accepted ways are: division of labor, leadership, incentive reward. Other accepted ways are: authority with responsibility, transfer of skill, task work. These accepted ways are the result of societal development. Such accepted ways from societal development are resistive to change, universal in application, and imperative to success, and therefore such management fundamentals are regarded as laws. The investigation shows the discovery of these laws and the determining quantitative factors for them.

Part II sets forth forty-three laws of manufacturing management with supporting citations.

A Research in the Elements of Metal Cutting

By ORLAN W. BOSTON

Associate-Professor of Shop Practice and Director Engineering Shops, University of Michigan

THIS paper gives an account of an investigation in the fundamental elements of metal cutting conducted in the Machine Tool Laboratory at the University of Michigan. The object of the investigation was to determine a relation between the force on the tool in the direction of cut for a constant cutting speed of 20 feet per minute and the degrees of tool sharpness, the various tool angles, the width and depth of cut, and the physical properties of the materials cut. Nine representative types of material were cut, including three carbon steels, three alloy steels, brass, and annealed and unannealed cast iron. The cutting was confined to straight-line motion on a planer, and the tools used were of the end-cutting type. No cutting fluids were used, and but one element was varied at a time.

The results show that the clearance angle has no influence on the force on the tool so long as the tool does not drag on the work, that the force on the tool remains constant for a wide variation of keenness of cutting edge, and that, for thick chips, particularly, the tool edge may be rounded to $^1/_{64}$-in. diameter without appreciable increase in the cutting force. It is also shown that the cutting force on the tool is reduced in direct proportion to the increase in front rake angle, all other factors remaining constant. It is shown that thick chips are removed more efficiently than thin chips, and that narrow chips are removed more efficiently than wide chips. The results also indicate that there is an apparent relation between some of the physical properties of the metals and their machinability or the cutting force on the tool for the carbon steels in one group, the alloy steels in a second group, and cast iron in a third group.

A bibliography on metal cutting has been made a part of the paper to enable those interested in the subject readily to locate those articles of interest or value to them.

Worm-Wheel Contact

By EARLE BUCKINGHAM

Professor of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

THE object of this paper is to show how any worm-wheel contact condition can be determined by analysis and to point out in particular the probable influence of the nature of the contact lines between a worm and a worm wheel upon the lubrication conditions, efficiency, and load-carrying ability. Analyses of three helicoids are made and their equations given.

The first of these, a convolute helicoid, had its generatrix tangent to a cylinder of any diameter concentric with the axis of the helicoid. The second, a screw helicoid, had its generatrix passing through the axis of the helicoid, and was one limiting case of the first, with the diameter of the base cylinder a concentric cylinder of such diameter that the helix angle at this diameter was the same as the angle of the generatrix with a plane perpendicular to the axis. The conjugate action of racks is discussed and equations given. An analysis of worm contact is made. Contact lines of screw helicoids used as worms and those of involute helicoids used as worms are discussed. Contact lines of screw helicoids with large helix angles, and involute helicoids with large helix angles are also treated.

Heat Transfer for Forced Flow of Air at Right Angles to Cylinders

By E. L. CHAPPELL AND W. H. McADAMS

Respectively, Research Assistant, Research Laboratory of Applied Chemistry, Department of Chemical Engineering, Massachusetts Institute of Technology, and Associate Professor of Chemical Engineering, Massachusetts Institute of Technology

FOR air flowing outside and at right angles to single cylinders, published data are available covering extreme ranges of 120-fold for the coefficient of heat transfer, 250-fold for mass velocity, 1800-fold for diameter, and nearly 4-fold for film temperature in degrees fahrenheit absolute. Of the theoretical equations proposed by Boussinesq and King, the latter is far more in accord with these data. At the lower temperatures the theoretical King equation gives predicted values in surprisingly good agreement with the data, in view of the rather questionable assumptions made during its derivation. The empirical equations of King for wires and of Rice for pipes agree well with the experimental values from which they were derived, but are not satisfactory when extrapolated to conditions for which they were not designed.

The method of plotting suggested by Davis has considerable promise, as does the rather complicated method of Rice involving the mean diameter of the effective film. No simple method was found for perfect correlation of the exact effect of each of the various factors. However, an empirical equation was developed and is recommended for practical use. For the high temperatures, where the exact effect of temperature is uncertain, the correction term for temperature was so chosen as to predict low rather than

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high values of the coefficient of heat transfer. The empirical equation involving the various factors is plotted in one of the figures accompanying the paper, thus making it unnecessary to substitute the values of the various factors in the recommended equation.

Data for staggered pipes are rather meager, but for a given mass velocity, diameter, and film temperature the coefficients are somewhat higher than for single pipes. A simple method is suggested for estimating the increase due to staggering.

Steam-Condenser Practice and Performance

BY F. J. CHATEL

Technical Engineer of Delray Plant, The Detroit Edison Co., Detroit, Mich.

THIS paper presents a general idea of steam-condenser practice and performance in the four plants of the Detroit Edison Co. The condenser performances from the original installations to those of the present time show a marked improvement. This indicates that condensers of the single-pass type with a range of from 0.95 to 1.05 square feet of surface per kilowatt of turbine capacity should be considered good practice. Their performance seems to outweigh the fact that a somewhat larger amount of water is necessary for this type than for a two-pass condenser or a condenser having more tube surface.

The Plastic Behavior of Metal in Drawing

BY C. L. EKSERGIAN

Research Engineer, Budd Manufacturing Co., Philadelphia, Pa.

DRAWING, unlike other classes of engineering work, has proceeded mostly as an art rather than a science. The empirical method has of necessity been the basis of advancement due to the limited knowledge of the attending phenomena.

The purpose of this paper is to foster the application of analysis to drawing as an aid to subsequent development. Toward this end no attempt has been made to set forth any concrete analysis since the subject is regarded as too complex for such a discussion at present. However, as a preliminary step in this direction an attempt is made to outline a manner of attack by which a proper conception of the phenomena may be realized. For the present a general discussion is made of the manner of working the metal with reference to its state and behavior in comparison to that found in drawing. A survey of the conditions observed in the forming of a stamping is also made which includes a report of certain experimental investigations which were conducted by the author.

Measurement of Static Pressure

BY CARL J. FECHHEIMER

Research Engineer, Power Engineering Department, Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

THE paper describes a new instrument for measuring static pressures in air-flow determinations. Made in the form of concentric brass tubes, the outer of which is 1/4 in. in diameter, the instrument is easily introduced into air ducts through small openings, such as bolt holes. Pressure is communicated to manometers through two holes, one to the inner tube and the other to the concentric space between the tubes, about 78.5 deg. apart. The instrument is held perpendicular to the flow in such a manner that the direction of flow bisects the angle between the axes of the holes. In this position, which can be determined by balancing the pressures on one manometer, the reading on a second manometer gives the static pressure. The instrument has less error in turbulent flow than other types.

Stresses Occurring in Walls of an Elliptical Tank Subjected to Low Internal Pressure

BY WILLIAM F. FRAME

Westinghouse Electric & Manufacturing Co., Sharon, Pa.

THE paper describes a test made on an elliptical tank, and an analysis is presented, based on experimental data, from which the stresses set up in the walls may be calculated. To account for the fact that the tank appeared stronger then was to be expected from usual assumptions, it was assumed that the wall acted as a beam supported at the top and bottom of the tank. The analysis from this point of view yields results which check the experimental data with reasonable accuracy.

Rough Turning, with Particular Reference to the Steel Cut

BY H. J. FRENCH AND T. G. DIGGES

Respectively, Senior Metallurgist and Assistant Scientist, Bureau of Standards, Washington, D. C.

TESTS described in this report extend to current commercial high-speed tool and structural alloy steels certain portions of Taylor's original investigations in rough-turning carbon steels. They were made primarily to show the effect upon tool performance of variation in chemical composition and mechanical properties of the steel cut, and accordingly include lathe tests on carbon, nickel, low- and high-chromium, chromium-vanadium, chromium-molybdenum and nickel-chromium steels having tensile strengths between 65,000 and 195,000 lb. per sq. in. However, many of the tests with the customary high tungsten-low vanadium steel tools were duplicated with low tungsten-high vanadium or cobalt high-speed steel tools, and there is included a partial study of the effects of cutting speed, feed, depth of cut, and coolants upon tool life and the power required in cutting. Graphical representation of results is employed, wherever it is found possible, to show the laws of cutting.

Ideal Gas-Engine Cycles

BY ROBERT C. H. HECK

Professor of Mechanical Engineering, Rutgers College, New Brunswick, N. J.

THE purpose of this paper is to promote the use, with the internal-combustion engine, of the ideal performance as a standard of comparison, by making that standard almost as readily convenient as is the Mollier chart for the steam engine. This purpose is accomplished in two steps: (*a*) developing a working chart that combines in one the temperature-entropy diagram and a diagram of internal energy and total heat on entropy, in which any horizontal line is a line of constant temperature, constant energy, and constant total heat; and (*b*) showing by trial upon representative examples that this chart, based on the properties of an average gas mixture, gives essentially correct output for any working mixture within the range of gas-engine practice.

Avoiding the common type of chart, with its confusing multiplicity of curves, the present scheme employs the principle of moving curves, carried by templets. The chart carries one curve of constant-volume and one of constant-pressure heating, with horizontal scales of volume and pressure and vertical scales of energy and total heat or "enthalpy." These are so disposed that any problem can be solved by construction upon a separate working sheet, laid down across the chart, which will serve as a permanent record of the solution.

Important features of the paper are found in Figs. 9 and 10 on the specific heats of working mixtures, Figs. 11 and 12 for the general idea of chart and method, and Figs. 20 and 21 for typical solutions.

Work-Hardening Properties of Metals

BY EDWARD G. HERBERT

Edward G. Herbert, Ltd., Manchester, England

IT IS the principal object of this paper to bring into correlation with the operation of cutting tools certain groups of well-established and generally recognized facts, the chief among them being: (1) the fact that metals are hardened by any process which deforms them so as to cause a permanent change of shape while they are at low or moderate temperatures, a process which is generally referred to as "cold work;" (2) the fact that metals are

deformed and are therefore hardened by cutting tools; (3) the fact that heat is generated by deformation of metals and in a pre-eminent degree by metal-cutting operations; and (4) the fact which has now been known for some time, that the degree of hardness induced by working metals with cutting tools or otherwise is greatly influenced by the temperature at which the deformation takes place.

An attempt is made to show the bearing of these correlated facts on the resistance offered by metals to the cutting tool, and on the rate of wear of the cutting tool.

A further and most important branch of the same subject, the relation between the temperature generated in cutting and the heat-resisting properties of "hot hardness" of the cutting tool, is barely touched upon.

The limiting factor in the rapid removal of metal and therefore in the productivity of the metal-working industries is, ultimately, the temperature generated in cutting in relation to the capacity of the cutting tool to withstand high temperatures. The present work deals with the heat-producing properties of the work rather than with the heat-resisting properties of the tool.

The Emergency Stops of the Gearless Traction Elevator at Terminal Landings

By F. HYMANS, NEW YORK

Mechanical and Electrical Engineer, Otis Elevator Co., New York, N. Y.

THIS paper is confined to an investigation of the oil buffer and the limit switch. Part I gives a short description of these and allied devices, while Part II gives a theory of the oil buffer, developed by the author, which makes possible the complete calculation of the properties of a given buffer if struck by a free weight at a given speed. In Part III a very useful and simple concept, is introduced under the name of "the equivalent system," by means of which the problems in Part IV are quickly disposed of with no greater difficulties than the application of first principles. Part IV is divided in four sections. The first is an investigation of the stop of an elevator when the limit switch is opened; the second an investigation of the stop of an elevator when brought about by the action of the buffer alone; the third an investigation of the stop of the elevator with buffer and limit switch coöperating in the usual sequen e of pra tice. One important feature of Part IV is the proof it furnishes that the required amount of top clearance can be readily calculated for any given emergency.

Since the emergency stops at high speed are generally associated with slack hoist rope, Part V develops formulas for determining the stresses upon the subsequent fall of the ascending member to pick to the slack. In it will be found the reason why present methods of field testing are not so infrequently accompanied by a failure of the shaft of the machine and often make a realignment necessary.

The Distribution of Belt Creep and Slip

By R. F. JONES

Research Engineer, Dept. Experimental Engineering, Leather Belting Exchange Foundation, Cornell University, Ithaca, N. Y.

SINCE the famous experiments of Wilfred Lewis a great deal of research has been done on belting problems in this country and abroad in order to obtain more engineering data and to improve the finished product, until today the belts themselves are better, and our knowledge of their applications is greater, than ever before. However, there is one phase of this subject which has been more or less neglected, and that is the distribution of slip around the pulley. The theories of Professor Bird and others on belt creep have been confirmed in a small way on lecture-room apparatus, and Fieber and Kammerer of Germany have made some experiments on larger belts. But there still seems to be an absence of data, especially on domestic belts of standard construction. The purpose of this paper is to describe the author's experiments on slip distribution, using standard domestic belts, and to set forth the conclusions which he reached.

The Lubrication of Waste-Packed Bearings

By G. B. KARELITZ

Westinghouse Research Laboratory, East Pittsburgh, Pa.

SINCE there is little published information in the technical literature on the mechanism of waste-packed bearings, this paper, based on results of an investigation on this subject made by the Westinghouse Electric & Mfg. Co., will be of interest. It discusses the feeding of oil through waste and the existence of a load-carrying oil film in such bearings as essential for their proper performance. It gives observations on the friction and temperatures of these bearings and on the importance of proper packing to insure sealing the window by oil-saturated waste, and also discusses the existence of a critical oil lift when the seal is broken. The reason for occasional end wear and scoring of the ends of a shell during the running-in period of service is given.

Internal Friction in Solids

By A. L. KIMBALL AND D. E. LOVELL

Both of Research Laboratory, General Electric Co., Schenectady, N. Y.

IN CONNECTION with a test devised to determine quantitatively the amount of friction within the metal of a steel shaft, it was found that the internal frictional forces were totally unlike those of a viscous fluid, as assumed by many investigators, where the forces are greater the more rapid the deformation. Instead of this, the dissipative forces were found to be the same whatever the speed of deformation. The apparatus with which the tests were conducted is described, and the results are tabulated. Equations relating to the variables involved are derived in the analysis of the problem.

Heat Transmission from Condensing Steam to Water in Surface Condensers and Feedwater Heaters

By W. H. McADAMS, T. K. SHERWOOD, AND R. A. TURNER

Respectively, Associate Professor of Chemical Engineering; Research Associate, Dept. of Chemical Engineering; an Instructor, Dept. Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

NEW experimental data are presented for single-tube water heaters supplied with exhaust steam. These, together with various data from the literature, are analyzed by the graphical method of E. E. Wilson, by means of which the overall resistance to heat transfer, $1/U$, may be successfully resolved into its component parts. Furthermore, by employing a coefficient of 2000 for the steam side, and by using the equation of McAdams and Frost for the water-side coefficient, it is possible to predict the value of U for various water velocities and temperatures. These predicted values compare closely with published test data both for vacuum condensers and feedwater heaters operated with exhaust steam, covering a range of sizes from 80 to 50,000 sq. ft. For abnormal amounts of air or scale, proper allowances should be made by applying the resistance concept.

The equation previously published for the heat transfer on the water side is found to be satisfactory for vacuum condensers and exhaust heaters. However, in analyzing laboratory data for single-tube apparatus heated by steam materially above atmospheric pressure, it was found that this equation gave unduly conservative results, the discrepancy increasing with increase in steam pressure. This may be due to the boiling of the water on the inner wall of the pipe, to the evolution of dissolved air, etc. Fortunately, since commercial apparatus are usually operated either under vacuum or with exhaust steam, this complication is of minor importance.

Kinematics of Cams, Calculated by Graphical Study

By H. SCHRECK

Charge of Design, Combustion Utilities Corp., New York, N. Y.

THIS paper presents the application of graphical methods to the calculation of velocity and acceleration of cams. The theory of the graphical methods is explained, its application to problems comprising various shapes of cams is presented, and

changes in kinematic conditions due to variation in the shape of the cam are described. The results are shown in tables and plotted in graphs in order to present a comparison of the forces produced by the various cams. Particular care has been taken to describe the graphical methods in such a way that they can be readily employed in every-day work.

So far as the author is aware, no such demonstration and comparison of cams has thus far been published and it is his wish that this very simple graphical method may find wide employment with engineers who use cams in their work.

Stresses and Deflections in Large Dynamo Frames Due to Dead Load

By M. STONE

Research Laboratory, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

BECAUSE of the continued tendency to enlarge the sizes of electrical rotating machinery, and necessarily the dynamo frames themselves, some thought has been given to the mechanics involved. The analysis given in this paper is the result of an investigation made by the Westinghouse Electric and Manufacturing Company. Two assumptions are made as to frame support, namely: that they are either (1) simply supported, or (2) built-in. The actual condition is probably between the two, and measurements are being made to determine the relative accuracy of the suppositions. However, the first assumption, since it imposes the more severe condition, size of air gaps, etc., should be designed according to these results.

The solution is obtained by two methods: Lord Rayleigh's theory, utilizing Fourier's series to give the final distribution of bending moments and deformations; and the theorem of Castigliano, which is simple and easy to use but which gives less general results. The compatibility of the two is established.

Tables and equations are given in the paper which will permit the accomplishment of satisfactory designs of machines much lighter than now in use. No analysis is made of the effect of unbalanced magnetic pull, all such effects being under the control of the designer in fixing his allowable air-gap variation.

Properties of Boiler Tubing at Elevated Temperatures Determined by Expansion Tests

By A. E. WHITE and C. L. CLARK

Respectively, Director of Department of Engineering Research and Holder of Detroit Edison Fellowship, University of Michigan, Ann Arbor, Mich.

PRESENT-DAY boiler practice employs temperatures varying from 550 to 750 deg. fahr. and pressures of around 350 lb. per sq. in. There is a growing tendency, however, to increase both temperature and pressure, but little is known of the properties of metals at elevated temperatures, particularly when temperatures are maintained for long periods of time.

The investigation recorded in this paper sets forth the preliminary findings on 0.13 carbon-steel tubing when loaded at temperatures of 900, 1000, 1250, and 1500 deg. fahr.

Possibly one of the most significant features of the test is the fact that for temperatures of 1500 and 1250 deg. fahr., at least, the authors find that the proportional limit, as ordinarily determined, is not the criterion of stability. Therefore they suggest for engineering design that until more data are available, no regard be given to the present-day proportional-limit values for elevated temperatures; but if such are used, then an adequate factor of safety shall be employed.

Tests and Theory of Curved Beams

By A. M. WINSLOW and R. H. G. EDMONDS

Respectively, Associate Professor of Mechanical Engineering, University of Washington, and Assistant Professor of Mechanical Engineering, University of Washington, Seattle, Wash.

DESPITE the fact that curved beams comprise such important machine elements as crane hooks and punch frames, previous laboratory tests have been, in general, of meager scope and uncertain interpretation. The laws of stress distribution, therefore, are subject to diverse opinion among prominent engineers. The present tests consist of strain-gage observations at several points throughout the cross-sections of large steel specimens, determining complete strain curves. Radial strains, apparently not previously investigated, are definitely measured and a simple working theory of radial stress is developed. Stress in a radial direction is shown to be a vital factor in the design of curved beams of certain proportions. Finally different theories of circumferential stress are investigated, both by comparison with tests and by analysis, prominent fallacies are pointed out, and a more logical fundamental hypothesis advanced in support of the theory adopted.

Influence of Radiation, in Coal-Fired Furnaces, on Boiler-Surface Requirements and a Simplified Method for Its Calculation

By W. J. WOHLENBERG and E. L. LINDSETH

Respectively, Associate Professor of Mechanical Engineering, Sheffield Scientific School, Yale University, and Member of Test Department, Cleveland Electric Illuminating Company, Cleveland, Ohio

THIS paper includes a simplified method of dealing with the energy problem of the boiler furnace. Its application yields information concerning that division of total surface between cold furnace walls and convection zone which results in the greatest overall energy absorption. The influence of fuel type, air preheat, and certain other factors on furnace conditions and surface requirements are also discussed.

Accuracy of the V-Notch Weir Method of Measurement

By D. ROBERT YARNALL

Yarnall-Waring Co., Philadelphia, Pa.

IN 1912, at the annual meeting of the Society, the author presented a paper on the subject, The V-Notch Weir Method of Measurement, and now after fourteen years of further experience with such weirs, he presents a second paper dealing more particularly with the degree of accuracy which one can count upon when using this method of measuring fluids.

The author's company recently had occasion to build for the Philadelphia Electric Company a million-pound-per-hour maximum-capacity V-notch meter for their new Richmond Station, this meter to be used as a standard piece of testing apparatus for calibrating orifice and other types of meters used for measuring various rates of flow in this station. As it was necessary to guarantee accuracies of this meter of $\frac{1}{2}$ of 1 per cent over its entire range, whether using full 90-deg. weir plates or fractions thereof, it seemed advisable to make a special calibration of this large meter.

From the many tests which have been made with the apparatus described in the paper, the author is convinced that any one who uses the coefficients corresponding with any given head that are shown by the curves given in one of the figures, can obtain accuracies within $\frac{1}{2}$ of 1 per cent.

Contributors to this Issue

W. H. Blauvelt

William H. Blauvelt, author of the paper entitled The Distillation of Coal, was graduated from Lafayette College. After a few years' experience in the operation of iron blast furnaces he turned his attention to the production and use of gas, together with the many problems surrounding the efficient and economical use of coal. He was with the R. D. Wood & Co., of Philadelphia, Pa., for several years, in charge of the gas-producer department of that firm, selling producers and installing them for clients. He then spent three years in Montana in the copper smelters, improving the metallurgical practice, especially by the application of gas to the smelting operations. From this work he went to Syracuse, N. Y., in the employ of the Solvay Process Co. and the Semet-Solvay Co., first to install a large plant of Mond by-product-recovery gas producers similar to those in England. For over twenty years he was connected with the Semet-Solvay Co. in the development of by-product coke ovens and in the production of coke and by-products and the manufacture of gas for cities and for industrial uses. During this period he occupied the positions of chief engineer, general manager, and consulting engineer. For the last five years he has been in private practice in New York City as consulting engineer in matters relating to the utilization of coal, the manufacture of gas, coke, and its by-products, and in the construction and operation of gas and coke plants.

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J. Bonforte

John Bonforte, author of the Development and Construction of the Standard Army Parachute, was born in New York, November, 1898, and enlisted in the army in 1918, having seen service in France, Germany and Poland. He was graduated from New York University in June, 1925, having specialized in aeronautics. A month before graduation he went with the U. S. Air Mail Service as mechanic on the construction crew on the night airway between New York and Cleveland. In November, 1925, he started working at McCook Field as junior aero-engineer on experimental parachutes. He is employed at present time by the Department of Commerce as extension superintendent surveying contract air-mail routes for the location of beacons and emergency landing fields on night airways.

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C. H. Bromley, who writes on New Methods of Lubricating Steel-Mill Machinery, was born in Adams, Mass., in 1888. Practically all his early life was spent in power-plant work. From 1912 to 1920 he was employed as associate editor of *Power*. From 1920 to 1921 he was connected with the Richardson-Phoenix Co., Milwaukee, Wis. From 1921 to 1926 he was manager of the engineering sales division, S. F. Bowser & Co., Fort Wayne, Ind., becoming assistant to the president in 1926. He has specialized in lubrication engineering from 1920 to 1926.

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F. L. Browne has been in charge of the wood-finishing investigations of the Forest Products Laboratory since its inception in 1922. He was graduated from Cornell University and after brief experience in the experiment station of the Du Pont Company and as a professor in a small southern college, he was appointed at the Forest Products Laboratory to take part in the development of water-resistant glues. Later he continued his studies in colloid chemistry in the graduate school of the University of Wisconsin. The last four years have been occupied at the Forest Products Laboratory in studying the finishing and painting problem of the wood users. Dr. Browne is a fellow of the American Association for the Advancement of Science and a member of the American Chemical Society. His paper is Wood Finishing—A Glance Ahead.

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H. V. Coes

H. V. Coes, vice-president and general manager of the Belden Manufacturing Company, was graduated from Massachusetts Institute of Technology. He was first associated with the Liquid Carbonic Co. as assistant to the president, and later became consulting engineering with the Searchlight Gas Co. of Chicago, and manager of the Chicago office of Lockwood, Greene & Co., of Boston. His next position was as principal engineer at the Boston office of the same concern. Following this he was appointed vice-president and general manager of the Sentinel Mfg. Co., of New Haven, later holding the position of industrial engineer with Gunn, Richards & Co., of New York, and then served in a similar capacity with Ford, Bacon & Davis of New York from 1917 to 1924. From 1917 to 1919 he was acting manager of the Platt Iron Works, of Dayton, O. Since October, 1924, he has been associated with the Belden Mfg. Co.

Mr. Coes assisted in the design, and built and operated the largest carbonic-acid plant in the world at Cambridge, Mass. He was co-inventor with C. A. Howard of a locomotive automatic stop and with G. I. Rhodes of a conveyor for handling hot material in a pneumatic conveyor without oxidation or reignition. He has reorganized munitions plants in Canada and in this country, and has contributed many articles to the technical press. He is a member not only of the A.S.M.E., but also of the Franklin Institute, A.A.A.S., Army Ordnance Association, and a number of clubs.

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C. S. Coler

Carl S. Coler, the author of the paper entitled Trades Training, is a graduate of Cornell University, class of 1911, in electrical engineering. He is manager of the educational department of the Westinghouse Electric & Manufacturing Co., president of the Westinghouse Technical Night School, and chairman of the technical department of the Westinghouse Club. He is a member of the Rotary Club and the Chamber of Commerce of Pittsburgh, Pa., the A.I.E.E., A.M.A., National Bureau of Economic Research, and the S.P.E.E.

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S. Daniels

Samuel Daniels, author of the paper, Fusion-Joining of Metallic Materials in Aircraft Construction, was born in Boston, Mass., in 1894, and received his A.B. degree in 1915. After graduation he was employed by the Framingham Machine Works, Framingham, Mass., and the Greenfield Tap & Die Corp., Greenfield, Mass. Later he was drafted by the Bureau of Aircraft Production, New York District, and represented that board at Duesenberg Motor Corp., Elizabeth, N. J. In 1919 he was moved to the Metals Branch, Material Section, Engineering Division, Air Corps, U. S. A., at McCook Field, Dayton, O., where he carried out research and development work both in ferrous and non-ferrous materials. In 1924 he became chief of the Metals Branch, with incidental charge of the foundry, which specializes in the production

of aircraft castings. He is a member of the A.I.M.E., British Institute of Metals, and American Foundrymen's Association.

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J. G. DEREMER

J. G. DeRemer, upon graduation from the University of California, immediately became associated with the Westinghouse Electric & Manufacturing Co. in San Francisco. In 1910 he became vice-president and assistant manager of the United Light and Power Co. of San Francisco. In 1914 resigning and becoming manager of the General Engineering Department of the American District Steam Co., North Tonawanda, N. Y. In May, 1917, he was appointed by Maj.-Gen. Geo. W. Goethals as technical assistant to the Ship Protection Committee of the U. S. Shipping Board at Washington, becoming a member of the committee later. At New London he worked in coöperation with the Naval Consulting Board and the Navy Department. Since the war Mr. DeRemer has been engaged in the practice of consulting engineering and research work. His paper is entitled Mercury Compressor Evolved from the Archimedes Screw Pump. He is a member of the A.I.E.E., A.S.M.E., and the A.A.A.S.

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Walter S. Edgar, at the present time employed by the Flood & Conklin Co. in the capacity of director of their lacquer department, received his education at the Colorado School of Mines, and in 1912 was connected with Stevens Institute. He was employed by the Hastings Pavement Co. as a chemist in 1915, and has been a sales engineer for the Atlas Cement Co., John Baker, Jr., and the Du Pont Co. He is the author of The Use of Wood Lacquer Finishes.

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H. A. EVERETT

Harold A. Everett, professor of thermodynamics in the department of mechanical engineering at Pennsylvania State College, was graduated from Massachusetts Institute of Technology in 1902. After several years with American and foreign shipyards, he returned to M.I.T. as a member of the faculty of the department of naval architecture and marine engineering, remaining there thirteen years and progressing through the various grades to that of associate professor. He then went to the post-graduate department of the U. S. Naval Academy at Annapolis as professor of marine engineering. In 1918 he became chief engineer and naval architect for the Union Shipbuilding Co. at Baltimore, Md., and remained with them until the yard closed in 1922, when he returned to Pennsylvania State College.

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E. F. GRUNDHOFER

E. F. Grundhofer was graduated from Pennsylvania State College in 1914 and received the degree of mechanical engineer at the same institution in 1920. He has been employed by the American Steel and Wire Co. at Donora, Pa., and was an instructor in mechanical engineering at the University of Colorado for several years. In 1917 he returned to Pennsylvania State College and is with the Engineering Experiment Station as assistant professor of experimental engineering doing research work in heat transmission. He presents The Guarded-Plate-Heater Method of Testing Low-Temperature Insulators Compared with Several Box Methods.

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A. C. FIELDNER

Arno C. Fieldner, Chief Chemist, U. S. Bureau of Mines, and Superintendent, Pittsburgh Experiment Station, has specialized in gas and fuel engineering and research ever since graduating from Ohio State University in chemical engineering in 1906. After engaging as industrial fuel engineer with the Denver Gas & Electric Company in Denver, Colo., he entered the Government service as assistant chemist in the Technology Branch of the U. S. Geological Survey in 1907 at Pittsburgh, Pa., to engage in fuel testing and research. In 1910 when the Bureau of Mines was created and took over this work, Mr. Fieldner was in charge of the fuels chemical laboratory and subsequently the gas laboratory also.

At the beginning of the World War he turned his attention to gas-mask research, first at Pittsburgh and later at the American University Experiment Station, Washington, D. C. He was later commissioned as a major in the Chemical Warfare Service and placed in charge of the gas-mask research section of the research division of the Chemical Warfare Service. After the war he returned to Pittsburgh as supervising chemist of the Pittsburgh Station and in June, 1921, was placed in entire charge of the station. In July, 1925, Mr. Fieldner was appointed chief chemist of the Bureau of Mines with headquarters at Pittsburgh, still retaining charge of the station as superintendent.

Mr. Fieldner is an active member of the Gas and Fuel Division of the American Chemical Society, the section on coal of the American Institute of Mining and Metallurgical Engineers, chairman of the Chemical Committee, American Gas Assocation, and chairman of the Committee on Coal and Coke of the American Society for Testing Materials. He has contributed a large number of articles on coal and gas analysis, testing, and research, and conducted the pioneer research on the ventilation of vehicular tunnels with respect to removal of carbon monoxide from automobile exhaust gases.

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F. G. HECHLER

F. G. Hechler received his B.S. degree from the University of Missouri in 1908 and his M.E., from the same institution in 1910. He then taught in the mechanical engineering department at Rensselaer Polytechnic Institute. In 1916 he became connected with the U. S. Naval Engineering Experiment Station, Annapolis, Md., as mechanical engineer, where he remained until 1919 when he joined the Vibration Specialty Co., of Philadelphia. Since 1922 he has been professor of engineering research at Pennsylvania State College and in charge of the engineering experiment station.

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R. H. HEILMAN

R. H. Heilman was born in Ford City, Pa., and received his professional education in the school of engineering of the University of Pittsburgh, receiving his E.E. degree in 1922. Mr. Heilman has been engaged in research on heat transmission since 1918 at Mellon Institute of Industrial Research of the University of Pittsburgh, where he now holds the position of Senior Industrial Fellow on the Heat Insulation Fellowship. He has been interested particularly in the determination of emissivity coefficients for bare and insulated pipes and in the development of apparatus for the determination of thermal conductivities of flat and cylindrical types of heat insulations, and in the development of high-temperature insulations and insulating cements.

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William R. Herod was born in Indianapolis, Ind., in February, 1898, and was educated at Yale University, being graduated with

a Ph.B. in 1918. He entered the testing department of the General Electric Co., in 1919, later being transferred to the construction-engineering department, devoting time to mechanical and electrical work with reference to tests of new equipment, engineering investigations in connection with central stations and factory power plants, and commercial engineering work.

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P. S. KENNEDY

Paul S. Kennedy, author of the paper entitled A Study of Varnish and Lacquer Finishes Exposed to Accelerated Breakdown Tests, was born in Rockland, Me., on September 26, 1888. Upon graduation from Worcester Polytechnic Institute in 1910 he entered the employ of the Murphy Varnish Company, Newark, N. J., and has been successively chief chemist, technical director, superintendent, and industrial sales manager of the company, of which he is at present vice-president. During the World War he was one of the original members of the Camouflage Corps, specializing in paint formulation. In this country and in France he was in charge of the Advance Camouflage Factory at Nancy. He has contributed much to the development of wood- and automobile-finishing materials, and methods in production. Mr. Kennedy is a member of the Society of Automotive Engineers as well as of the A.S.M.E.

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E. B. RICKETTS

E. B. Ricketts, Research Engineer, The New York Edison Co., was graduated from Millsaps College in 1901. He has been connected with the operating department of the above company in various capacities for over twenty years. He contributes the paper, Tests for Four Condensers.

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Osborn Monnett, who presents the paper entitled Present Status of the Smoke Problem, was born in Norfolk, Va., in 1876, and began active engineering in the stationary power-plant field in Ohio and in marine engineering on the Great Lakes. He later became identified with railroad work with W. & L. E. and C. R. I. & P., and also was an early student of chemistry and its relation to engineering, especially combustion. He was on the editorial staff of *The Engineer* of Chicago, and later associate editor of *Power*. At one time he was chief smoke inspector of the city of Chicago and wrote and lectured extensively on combustion, boiler, plant operation, and smoke abatement. He became engineer in conservation, U. S. Fuel Administration, Washington, D. C., and then directed at Salt Lake City and Grafton, W. Va., atmospheric surveys and an inquiry into low-temperature distillation of Utah coals for Bureau of Mines. Later he directed a smoke survey for Memphis, Tenn. In St. Louis he was consulting engineer for the Citizens Smoke Abatement League. Mr. Monnett specializes in combustion, boiler practice, and smoke abatement.

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E. C. MAGDEBURGER

Edward C. Magdeburger, author of the paper entitled The Modern Oil Engine, was born in Russia, January 1, 1886. He was graduated in mechanical engineering from the St. Petersburg Institute of Technology in 1909, and began his career of building Diesel engines at the Kolomna Iron Works. Since coming to this country in 1910 he has been connected with the Allis-Chalmers Co., Fairbanks-Morse Co., and Busch-Sulzer Bros. Diesel Engine Co. For the last five years he has been with the Navy Department as aide on Diesel engines.

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H. B. MELLER

H. B. Meller was born in Altoona, Pa., on May 26, 1878, and was educated at the University of Pennsylvania, being graduated with the degree of Engineer of Mines in 1910. From 1910 to 1923 he was a member of the faculty of his alma mater, being vice-dean from 1912–1914 and dean from 1914–1923. From 1923–24 he was a senior fellow in charge of air-pollution investigation at the Mellon Institute of Industrial Research. From 1920 to date part of his time has been spent as Bureau Chief, Bureau of Smoke Regulation, of the City of Pittsburgh. He is author of the paper on Smoke Abatement.

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N. N. Sawin was graduated in 1900 from the Technological Institute of St. Petersburg, and from 1900 to 1903 was engineer at the Putiloff Works in the same city. From 1903 to 1917 he was assistant professor and professor of applied mechanics in the Technological Institute. In 1921 he became connected with the Polytechnic Institute in Zagreb. At the present time he is research engineer in the Skoda Works in Czechoslovakia. He is author of the paper entitled The Theory of Milling Cutters.

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R. E. NEWCOMB

Robert E. Newcomb was born September 11, 1884, and graduated from Cornell University with the degree of Mechanical Engineer. Upon leaving college he entered the machine shops of the Deane Works of the Worthington Pump and Machinery Corp., and was successively promoted to foreman, assistant superintendent, and superintendent. Mr. Newcomb has frequently been delegated by his company to make special investigations and reports upon manufacturing and engineering problems and plant equipment. He belongs to a number of organizations, among which are: Industrial Relations Committee of the National Metal Trades Association, New England Foundrymen's Association, American Society of Mechanical Engineers, American Society of Testing Materials, and the American Society of Electrical Engineers. His paper is entitled, Vitalizing vs. Centralizing Organizations.

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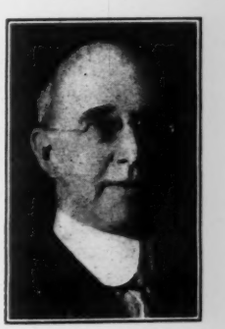

PERCY NICHOLLS

Percy Nicholls, the contributor of the paper entitled, Status of Heat-Transmission Data and Knowledge in the Refractory Field, was educated in England at the Leeds University and gained Whitworth and National scholarships. His earlier work was largely electrical engineering with the Westinghouse, General Electric, and Western Electric Companies, followed by positions as engineer of works for manufacturing concerns. He became associated with heat transmission in connection with a manufacturer of heat insulations, and acted as engineer and advisor for the Magnesia Association in connection with its general work and its special investigations at the Mellon Institute. He did special work on heat transmission for the laboratory of the American Society of Heating and Ventilating Engineers, and is at present acting as fuel engineer in charge of the fuel Section at the Pittsburgh Experiment Station of the U. S. Bureau of Mines.